BASES OF DESIGN OF OVERHEAD ELECTRICAL LINES ACCORDING TO GENERAL REQUIREMENTS OF EUROPEAN STANDARD EN 50341-1: 2001

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ABSTRACT: Basic requirements about reliability, security and safety conditions of the overhead electrical lines are presented in accordance with European Code EN 50341-1:2001. Actions on overhead lines and load cases on supports have been classified. Basic design assumptions used in analysis of lattice steel towers are announced and limit state method has been consistently introduced to structural design of overhead electrical lines.

Keywords: Overhead electrical line, structural design, limit states, actions on structures, steel supports

1. INTRODUCTION AND ESSENTIAL DEFINITIONS

The new European standard EN 50341-1 [1] provides a basis and general principles for the structural, geotechnical and mechanical design of overhead electrical lines in conjunction, in the case of steel structures, with Eurocode 3: EN 1993-1-1 [2] and EN 1993-3-1 [3]. The general principles of structural design are based on the limit state concept used jointly with the partial factor method. The values of the partial factors for actions and material properties depend on the type of structures and the type of limit state. Partial factors also depend on the coordination of strength envisaged for the lines.

In principle, there are two approaches used to determine the numerical values for actions, material properties and partial factors of safety. The first one, *General approach*, is based on the statistical evaluation of meteorological and experimental data and field observations. The second one, *Empirical approach*, is based on the calibration by a long and successful history of overhead lines construction. In practice, the two above approaches are used in combination.

In Poland, according to the National Normative Aspect: EN 50341-3-XX [4], the statistical approach is considered as giving additional, accessible numerical values for actions and material properties to the Empirical approach.

In order to achieve a better understanding of the definition of certain terms (by mechanical and electrical engineers), some essential definitions, according to International Electrical Vocabulary – Chapter 466 – Overhead lines: IEC 60050, are presented, as follows:

- *Electrical system* – all items of equipment, which are used in combination for the generation, transmission and distribution of electricity;
- *Mechanical system* – set of components connected together to form an overhead electrical line, e.g. conductors, supports, foundations, insulator strings and hardware;
- *Electrical reliability* – ability of a system to meet its supply function under stated conditions for a given time interval;

- *Structural reliability* – probability that a system performs a given purpose under a set of conditions over a reference period. Reliability is thus a measure of the success of a system in accomplishing its purpose;
- *Design working life* – assumed period for which a structure is to be used for its intended purpose with anticipated maintenance but without substantial repair being necessary;
- *Action* – force (load) applied to the mechanical system (direct action) or an imposed deformation caused by temperature changes, uneven settlement, etc. (indirect action);
- *Load cases* – compatible load arrangements, sets of deformations and imperfections considered simultaneously with defined variable actions and permanent actions for a particular verification;
- *Reference period* – period taking into account the design working life of the system or of one of its elements and/or of the characteristic value of an action;
- *Return period* – mean interval between successive recurrences of a climatic action of at least defined magnitude. The inverse of the return period gives the probability of exceeding the action in one year;
- *Safety* – ability of a system not to cause human injuries or loss of lives during its construction, operation and maintenance;
- *Security* – ability of a system to be protected from a major collapse (cascading effect) if a failure is triggered in a given component. This may be caused by electrical or structural factors;
- *Design situation* - set of physical conditions representing a reference period for which the design will demonstrate that the relevant limit states are not exceeded;
- *Clearances* – distance between two conductive parts along a string stretched the shortest way between these conductive parts; internal clearances – are between phase conductors and earthed parts such as steel structural elements and earth wires and also those between phase conductors; external clearances – are between phase conductors to ground plane, roads, buildings and installations;
- *Support* – general term for different types of structure that support the conductors of the overhead electrical lines;
- *Suspension support* – support equipped with suspension insulator sets;
- *Tension support* – support equipped with tension insulator sets;
- *Tangent support* – suspension or tension support used in straight line;
- *Angle support* – suspension or tension support used at angle point of a line;
- *Section (anchorage) support* – tension support with or without a line angle serving additionally as rigid point in a line to limit cascading;
- *Terminal (dead-end) support* – tension support capable of carrying the total conductor tensile forces in one direction;
- *Span length* – the horizontal distance between two adjacent supports;
- *Wind span* (of a support) – the arithmetic mean value of the lengths of adjacent spans;
- *Weight span* (of a support) – the horizontal distance between lowest points of conductors on either side of a support.

2. BASIC REQUIREMENTS

An overhead electrical line should be designed and constructed in such a way that during its intended life, it shall perform reliability, security and safety requirements. Moreover, the conditions of the public safety, durability, robustness, maintainability, environmental requirements and appearance of the structure should be considered and found satisfactory.

Reliability requirements are achieved by design according to: EN 50341-1 [1], EN 1990 [6], EN 1991 [7] and EN 1993 [2]. In accordance with the Polish National Aspects EN 50341-3-XX [4], it is decided to apply the reliability level 1 for overhead lines, i.e., the return period T of climatic actions is 50 years.

Security requirements correspond to special loads and measures intended to prevent uncontrollable progressive or cascading failures. It is essential that the failure is contained within or very close to the section where overloads occur. In order to prevent cascading failures, some simulated actions and loading conditions are provided.

Safety requirements are intended to ensure that construction and maintenance operations do not pose safety hazards to people. The safety requirements consist of all special construction and maintenance loads, taking into consideration the working procedures, temporary guying, lifting arrangement, etc.

When designing an overhead line using statistical approach, three different reliability levels may generally be considered, each corresponding to a given return period T of the characteristic value of the variable (climatic) actions:

- level 1 - T = 50 years,
- level 2 - T = 150 years,
- level 3 - T = 500 years.

Deviations from these levels may be made in accordance with the specific requirements for the project in question. However, the level selected shall at least correspond to a reliability of level 1 (T = 50 years), except for temporary constructions and for components installed temporarily (for example T = 3 or 10 years).

The yearly reliability of an overhead line (a structure) is roughly related to the return period T of the climatic actions and is between $(1 – 1/T)$ and $(1 – 1/2T)$, that for reliability level 1 is of 0.98 to 0.99, which can be considered as a minimum value.

An absolute reliability of an overhead line (as of each structure) will generally be difficult to determine. Therefore, reliability level 1 can be regarded as the reference reliability whereas the higher reliability levels are to be understood as relative to the reference one. Besides, the reliability of a structure depends on determination of resistance level of the structure.

In order to provide an overhead line corresponding to the requirements and to the assumptions made in the design, appropriate quality assurance measures during design and construction should be adopted. Quality assurance is described in EN ISO 9001.

The general principles of structural design of overhead line are based on the limit state concept used in conjunction with the partial factor method.

Limit state design shall be carried out by:

- setting up structural and load models relevant to ultimate or serviceability limit states, which are to be considered in various situations and load cases,
- verifying that the limit states are not exceeded when design values for actions, material properties and geometrical data are used in the model.

Design values are generally obtained by using characteristic or combination values in conjunction with partial factors, as defined in EN 50341-1 [1], EN-50341-3-XX [4] and in Eurocodes: 0, 1 and 3, i.e. in: EN-1990 [8], EN-1991 [7] and EN-1993-1-1 [2].

Ultimate limit states are those associated with collapse or with other similar forms of structural failure due to loss of stability, overturning, rupture, buckling, etc. Ultimate limit states concern the reliability and security of supports, foundations, conductors and equipment, as well as the public safety.

Serviceability limit states correspond to certain defined conditions, beyond which specified service requirements for an overhead line are no longer met. The serviceability requirements concern the mechanical functioning of supports, foundations, conductors and equipment, as well as the electrical clearances. Serviceability limit states include deformations and displacements that affect the appearance of effective use of the support including a reduction of electrical clearances, vibrations which cause damage to conductors, supports or equipment or which limit their functional effectiveness, and the damage which is likely to affect the durability of overhead line.

3. ACTIONS ON OVERHEAD LINES

3.1 Classification of Actions

An action, (*F*), is a direct action, i.e. force (load) applied to the conductors, insulators, supports and foundations or an indirect action, i.e. an imposed or constrained deformation caused, for example, by temperature changes, ground water, variation or uneven settlement, if applicable. Actions may have static or dynamic nature. Usually, with the exception of seismic area, actions on overhead lines are considered as static or quasi-static action, such as wind load, etc. In the design of overhead line supports and foundations, special attention should be paid to the extraordinary span length and slender supports.

In view of variation in time, actions on support of overhead lines are classified, as follows:

- *permanent actions (G),* i.e. self-weight of conductors and the effects of the applicable conductor tension at the reference temperature, self-weight of support foundations, fittings and fixed equipment, as well as uneven settlements of support;
- *variable actions (Q*), i.e. wind loads, ice loads, conductor tension effects due to wind and ice and temperature and other imposed loads; wind and ice loads as well as applicable temperatures are climatic conditions, which can be assessed by probabilistic methods (general approach) or on a deterministic basis (empirical approach); the vertical reaction from self-weight of the conductor at the support (the weight span) is affected by deviations from the reference state of the conductor tension due to conductor creep and temperature variations and is a variable action.
  Construction and maintenance loads including working procedures, temporary guying, lifting arrangement, etc., are variable actions with reduced reference period of these actions. Imposed loads arising from conductor stringing, climbing on the towers, etc., are assessed on a deterministic basis and refer to the safety aspect;
- *accidental actions,(A),* i.e. failure containment loads (at rupture of a conductor); avalanches, exceptional ice loads including unbalanced ice loads, etc. These relate to the security aspect.

Characteristic value of an action, F_k , it is main representative value used for limit state verifications.

The characteristic value of permanent action is its mean value, $G_k = G_{mean}$. For variable actions, the characteristic value, Q_k , corresponds to: either a nominal value used for deterministic based actions and in empirical approach, or an upper value with an intended probability of not being exceeded, e.g. wind and ice loads, during a reference period of one year. In the standard EN 50341-1 (2001), a value of probability *0.02* per year is assumed, i.e. the return period of climatic actions is *50* years for structures of probability level *1* . For accidental actions, representative value is generally a characteristic value, A_k , corresponding to a specified value.

Design value of an action, F_d , is expressed in general terms as: $F_d = F_k \gamma_F$, where γ_F is the partial factor for actions.

Combination value of a variable action Q is generally represented as a product of a combination factor and a characteristic value, ($\Psi_Q Q_k$), or directly by an action with a reduced return period. This combination value is considered to be the design value, to take account of a reduced probability of simultaneous occurrence of the most unfavorable values of several independent actions. Where the occurrence of actions is correlated with each other, this is reflected in the combination factor. In the standard EN 50341-1 [1], the combination factor for a variable action, Ψ_Q , is principally derived on the basis of a reduced return period and, therefore, includes the partial factor used in the Eurocode format as well as any other reduction factors.

Basic design condition of the ultimate limit state is:

$$E_d / R_d \leq 1 \quad \text{or} \quad E_d \leq R_d, \tag{1}$$

where:

- E_d – the total design value of the effect of actions, such as internal force or moment or a representative vector of several internal forces or moments,
- R_d – the corresponding structural design resistance associating all structural properties with the respective of structural design values.

3.2 Load Cases

The standard load cases are presented in Table 1.

For the design of conductors, equipment and supports including foundations in the ultimate limit state load case giving the maximum loading effect in structure and each individual member (and connection) should be considered. Conductor tensions should be determined according to the loads acting on the conductor in the defined load case. The components of the conductor tension at attachment points of the support, including the effects of vertical and horizontal angles, should be taken into account. If, initially, the circuits on a multi circuit support or the sub-conductors of bundles will only be partially installed, this condition shall be considered in the design.

Calculations shall be based on the real components of the vertical, transverse and longitudinal loads in various load cases. Weight of towers, conductors and accessories shall be taken into account in all load cases.

Table 1. Standard Load Cases

Design situation	No.	Description of a load case (conditions)	Temp. [°C]	Apply to
normal	0	Permanent actions of conductors, insulators and supports and foundations	+10 -5 -25 +40	all elements
	1	Extreme wind load normal to the line and at all other angles which may be critical to design	+10 -5	all elements
	2a	Uniform ice load on all spans	-5	all elements
exceptional (accidental)	2b	Ice loads unbalanced transversely (transverse bending): ice load equal to the characteristic value multiplied by the reduction factor $\alpha = 0.5$ on all the conductors on all cross-arms on one side only of the support but from other side without a reduction	-5	all supports
	2c	Ice loads unbalanced longitudinally (longitudinal bending): ice load equal to the characteristic value on all the conductor in one direction only from all cross-arms of the support multiplied by the reduction factor $\alpha_1 = 0.35$ and in the other direction by the reduction factor $\alpha_2 = 0.7$		
	2d	Ice loads unbalanced torsionally (torsional bending): ice load equal to the characteristic value on all the conductors on all cross-arms on one side only on the support and in one direction of the line multiplied by the reduction factor $\alpha_3 = 0.35$ but for all remaining conductors multiplied by the reduction factor $\alpha_4 = 0.7$		
normal	3	Combined ice and wind loads, where joined effect E_d should to be determined in two main combinations: I. $E_d = E_d(1{,}0Q_{Ik}, 0{,}4Q_{Wk})$, II. $E_d = E_d(0{,}35Q_{Ik}, 0{,}7Q_{Wk})$	-5	all supports (elements)
normal (construction and maintenance)	4a	Actions equal of 2/3 value of one side release of tension in the conductors with uniform ice loads on all spans	-5	tension (anchorage) supports
	4b	Action of full one-sided release of tension in the conductors with uniform ice load (at the attachment points)		cross-arms and other elements of support on which less than three conductors are tension supported
	4c	Construction and maintenance loads appropriately to the method of erection and concentrated loads related to the weight of linesmen, working platform, etc.		all supports
exceptional (accidental)	5	Action equals of full one-sided release of tension in any one earth wires or phase conductors at the attachment point (torsional load)	-5	tension (anchorage) supports

Note: In each load case, it should take into account the permanent actions (No.0), e.g., self-weight of the tower, conductors, insulators, fittings as well as the effect of the applicable conductor tension at the reference temperature. Moreover, in suitable load cases, the conductor tension effect due to wind and ice and temperature deviations from the reference temperature should be taken into consideration.

The main variable actions on conductors, insulators and supports are: wind or icing applied in adequate temperature, as well as combination of wind and ice loads. Wind and ice actions directly on supports (towers) shall also be considered.

The following types of supports are distinguished in accordance with their function:

- *suspension supports and angle suspension supports, (S and SA),*
- *tension (anchorage) supports and angle tension(anchorage) supports, (T and TA),*
- *dead-end (terminal) supports and angle dead-end (terminal) supports, (D and DA).*

Security loads are specified to give minimum requirements on the longitudinal and torque resistance of the supports by defining failure containment loads. The loads considered are one-sided release of tension in a conductor and conventional unbalanced overloads (icing), respectively.

For control of adequate reliability and functions under service conditions of the overhead line, load cases ought to be defined in the National Normative Aspects (NNA for each European country) to reflect national practices (special national conditions and national complements).

In Poland, the NNA: EN 50341-3-XX [4] introduces in formal Empirical approach to define actions on overhead electrical lines, but with the use of statistical data of self-weight of structure components, wind speed and ice loads and limit state format for the design of structures. In practice, the two above approaches are used, i.e. Empirical and General approaches in combination.

3.3 Partial Factors for Actions γ_F and for Resistance (Material) γ_M

Partial factors for actions, $\gamma_{F,}$ and for resistance, $\gamma_{M,}$ according to EN 50341 -3-XX (2006) are presented in Table 2 and Table 3, respectively.

Table 2. Partial Factors (γ_F) and Combination Factors (ψ_F) for Actions

Design situation	Symbol	Factors
Normal, construction and maintenance load cases:		
• Permanent loads	γ_G	1.1; (0.9 when favorable)
• Variable actions (climatic loads)	γ_Q, γ_W, γ_I	1.3
• Combination of wind and ice actions	ψ_I and ψ_W, properly	1.0 and 0.4 or 0.35 and 0.7
Exceptional load cases:		
• Permanent loads	γ_G	1.0
• Variable actions	γ_Q	1.0
• Accidental action	γ_A	1.0

Table 3. Partial Factors for Resistance (γ_M)

Part of structure	Reference limit	Kind of resistance of an element	Symbol	Factor γ_M
Steel supports	f_y	Resistance of cross-section	γ_{M0}	1.0
	f_y, E	Resistance of members to buckling	γ_{M1}	1.10
	f_u, f_y	Resistance of net-section at bolt holes	γ_{M2}	1.25
	f_u	Resistance of bolted or welded connections	γ_{Mj}	1.25
Metal conductors	Characteristic resistance R_k	Resistance with full icing	γ_{MCI}	1.25 1.40*
		Resistance with 50% of icing	γ_{MC2}	1.90
		Resistance in case of III tightening degree	γ_{MC3}	1.80
		Resistance with 50% of icing and in case of III tightening degree, simultaneously	γ_{MC4}	2.80
Insulators	Guarantee resistance	Resistance of insulator	γ_{Mins}	2.00
Fittings	Characteristic resistance	Resistance of fittings	γ_{Mf}	1.60
Note: (*) if conductor included optical fibres				

4. STEEL SUPPORTS (TOWERS)

4.1 Basic Design Assumptions

Supports of overhead electrical lines exceeding AC 45 kV are usually designed as lattice steel towers. Exemplary silhouettes of steel towers for high-voltage overhead lines are shown in Figure 1 and pictures of suspension, tension angle and tension transposition supports are shown in Figures 2, 3 and 4, suitably.

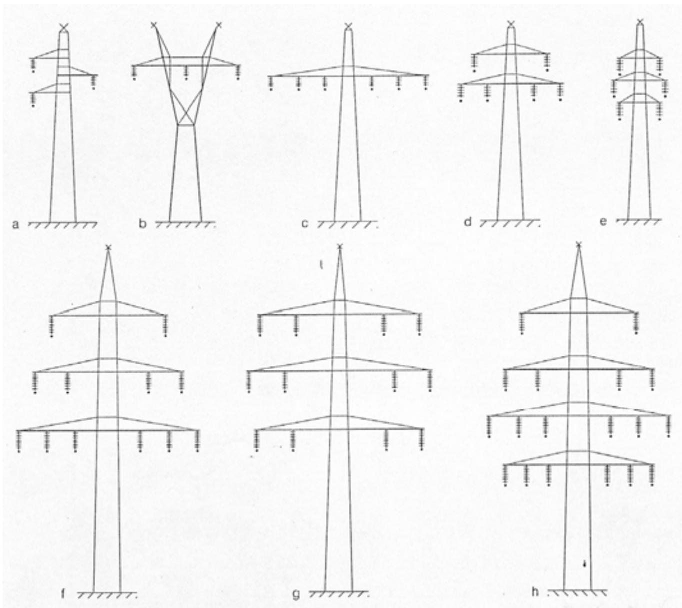

Figure 1. Exemplary Silhouettes of Steel Towers for One or Multi-circuit towers of High- and Extra-high Voltage Lines

Figure 2. View of Suspension Support

Figure 3. View of Angle Support with Tension Insulator Sets

Main assumptions used in global analysis of lattice steel towers are, as follows:

- The internal forces and moments in a statically indeterminate structure shall be determined using elastic global analysis. Lattice steel towers are normally considered as pin jointed truss structures. If the continuity of a member is considered (in a joint point), the consequent secondary bending stresses may generally be neglected. Approximate calculation of member loads by considering tower panels as two-dimensional trusses is acceptable, providing the equilibrium conditions are satisfied. It shall be verified that bracing systems have adequate stiffness to prevent local instability of any parts.
- The internal forces and moments may generally be determined using either first order theory (initial geometry of a structure) or second order theory (actual geometry with the influence of the deformation of the structure). Normally, first order theory is used for the global analysis of self-supporting lattice towers.
- Elastic global analysis shall be based on the assumption that the stress-strain behaviour of the material is linear, whatever the stress level. The assumption may be maintained for both first-order and second-order elastic analyses.
- Three types of lattice steel tower members are considered: main legs and chords, bracings and secondary members (often referred to as redundant members). The secondary members are considered not to be loaded directly by external actions, and the local stability of members carrying loads should be ensured. In the global analysis network, the redundant members can normally be neglected.
- Bending moments due to normal eccentricities are treated in the selection of buckling cases. Bending moments caused by wind loads on individual member are generally negligible, but they need to be considered in the design of slender bracings or horizontal edge members of towers.

Figure 4. View of Transposition Support with Tension Insulator Sets

4.2 Design Resistance of Lattice Tower Members

Most of lattice tower members are designed by checking their buckling resistance and the proper confession of their effective length (buckling length) and their slenderness is a key question.

Until the process of harmonization of the National and European standards is completed, it is possible to use either Polish standard PN-B-03205 [12] with NNA for Poland, EN 50341-3-XX [4], or Annex *J* of EN 50341-1 [1] for the design of overhead line steel structures in Poland.

There are several different configurations of tower members, which are commonly used in lattice towers, and each requires separate consideration about their carrying capacities (resistance). The buckling length, l_e, and hence the capacity of compression member depends on the type of bracing used to stabilize the member.

Generally, according to Eurocode 3 and EN 50341-1-1 [1], checking of buckling resistance of a member is shown below:

$\lambda = l_e / i_y$ or $\lambda = l_e / i_{\min}$ - slenderness of the member, (2)

where: $l_e = l_y$ or $l_e = l_{min}$ – distance between points of the lattice net,

$\overline{\lambda}_i = \frac{\lambda}{\pi}\sqrt{\frac{f_y}{E}\frac{A_{eff}}{A}}$ - relative slenderness (slenderness ratio) for flexural buckling;

for angle profiles with equal legs, the relative slenderness for flexural torsional buckling may be calculated approximately using the formula:

$$\bar{\lambda}_p = \frac{5}{\pi}\frac{b}{t}\sqrt{\frac{f_y}{E}\frac{A_{eff}}{A}},$$

A_{eff} – effective cross-section of the member taking into account the local instability of cross-section.

For members in axial compression, the design value of the compression force, N_d , divided by design value of the buckling resistance, $N_{R,b}$, shall satisfy the condition:

$$N_d/N_{R,b} \leq 1, \tag{3}$$

where:

$$N_{R,b} = \chi A_{eff}\frac{f_y}{\gamma_{M1}}, \tag{4}$$

$\chi = \dfrac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}_i^2}}$ - reduction factor (buckling factor) but $\chi \leq 1$,

$\phi = 0{,}5[1 + \alpha(\bar{\lambda}_i - 0{,}2) + \bar{\lambda}_i^2]$ - parameter of buckling curve,

α – imperfection factor depends on accepted buckling curve: *a*, *b*, *c* or *d*, equal approximately: 0.21; 0.34; 0.49 and 0.76.

Design of the support should be done by calculation only or by calculation validated by a full-scale loading test. If the design is done by calculation only, the appropriate buckling curve to be used shall be the curve *c*, that is α = 0.49; if design is done by calculation and validated by documented full-scale test , the appropriate buckling curve to be used should be the curve *b*, that is α = 0.34.

Connections should be capable of resisting their applied loads. The resistance of a connection shall be determined on the basis of the resistances of the individual fasteners or welds. Connections are generally considered as nominally pinned.

4.3 Required Electrical Clearances

The height of tower, its silhouette and overall dimensions depend on required electrical clearances in detail presented in electrical part of the EN 50341-1 [1]. Guiding information in this range, for the use of steel structures designers, is presented in Table 4.

Table 4. Minimum Air Clearances

Highest system voltage [kV]	D_{el} [m]	D_{pp} [m]	Clearance to ground [m]	Clearance to trees [m]	Clearance to buildings [m]
45/52	0,60	0,70	5 + D_{el}	2,5 + D_{el}	Depending on kind of building 2,5 + D_{el} ÷ 10 + D_{el}
110/123	1,00	1,15			
220/245	1,70	2,00			
400/420	2,80	3,20			

Remarks:
D_{el} – minimum air clearance required to prevent a disruptive discharge between phase conductors and objects at earth potential,
D_{pp} – minimum air clearance required to prevent a disruptive discharge between phase conductors.

It is not permitted to cross over the apartment buildings, factory buildings, office buildings, etc. by overhead lines exceeding AC 110 kV.

5. CONCLUSIONS

The new European standard (EN 50341-1 [1]) consistently introduced the limit state concept to structural design (mechanical aspect) of overhead electrical line elements, i.e. conductors, insulators, supports and foundations. The electrical aspect is also taken into consideration, first of all in serviceability limit state, through the requirements of minimum electrical clearances within the span, at the support and to the ground, which have fundamental influence on tower height and cross-arms dimensions. The possibility of combined wind and ice load are considered respective of load cases, as well as unbalanced ice loads on conductors: longitudinally, transversely and torsionally in relation to the tower. These complex requirements based on probabilistic approach (characteristic and design values of the actions and resistances of structures) and empirical approach (realistic load cases and failure cases) increase the reliability of overhead electrical lines.

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