DESIGN CHALLENGES FOR DISTRIBUTION OVERHEAD LINES SUBJECT TO HIGH IMPACT LOW PROBABILITY EVENTS

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ABSTRACT
The severity and frequency of weather events occurrence in Brazil, such as storms, windstorms and tornados, has increased in the past few years and presented important effects on the reliability indicators of main Brazilian utilities, directly impacting their operation and maintenance costs.

This paper presents the studies and efforts of CELES D, a utility in southern Brazil, in the pursuit to reduce the impact of occurrences originated from high impact low probability weather events, in order to reduce the time for electrical system restoration, improvements in service to its customers and the consequent reduction in reliability indicators.

INTRODUCTION
The consequences for the distribution lines in the occurrence of large magnitude meteorological phenomena are high mechanical stress and vibration that impair their operation, reflecting the performance of SAIDI and SAIFI continuity indicators.

The most common causes of occurrences in medium voltage lines, in times of storm, are caused by falling trees and objects (plates, tiles, structures or tree branches) launched on conductors, causing the rupture of them, short circuits and, in some cases, the break of poles.

CELES D to minimize the effects of atmospheric phenomena on their distribution networks, reduce the number of outages and to reduce recovery time, and yet, considering the necessity imposed by the regulator to improve the reliability indicators of its electricity distribution lines, decided to invest in a R&D Project, whose objective is the redefinition of the:

a) values of meteorological parameters;
b) methodology for calculating the mechanical stresses acting onto the conductors and overhead lines structures, considering the effects of extreme winds, characterized as winds of high intensity and short duration burst;
c) mechanical stresses acting on the conductors and structures in the occurrence of falling trees onto the conductors through simulations by finite element method;
d) use of mechanical fuses to promote mechanical coordination of networks in the occurrence of tree falling, protecting the post and conductors.

The results of these studies allowed Celesc to develop new standards for overhead distribution networks, mechanically coordinated in order to avoid or minimize the impact of occurrences during storms.

CLIMATE PARAMETERS
At this stage of research studies have been conducted to characterize the major weather events that take place in Santa Catarina and made statistical treatment of the wind speed data measurements at meteorological stations to obtain the mapping of the concession area of Celesc and setting values of meteorological parameters to be used in mechanical calculations.

Figures 1 and 2 show on the map of the state of Santa Catarina the wind lines of same speed referred a 10-minute and 3 seconds winds, respectively, to wind return period of 50 years, determined by the methodology for forecasts of annual wind speed limits based the statistical distribution of extreme values Gumbel.
Table 1 presents a summary of the characteristic values of 10 minutes wind speeds (maximum wind) and 3 seconds winds (wind gust) representing the Santa Catarina State, calculated for return periods of 50, 100 and 150 years.

<table>
<thead>
<tr>
<th>Return Period</th>
<th>Wind Speed (10 minutes)</th>
<th>Wind Speed (3 seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 years</td>
<td>105 km/h</td>
<td>170 km/h</td>
</tr>
<tr>
<td>100 years</td>
<td>110 km/h</td>
<td>180 km/h</td>
</tr>
<tr>
<td>150 years</td>
<td>120 km/h</td>
<td>190 km/h</td>
</tr>
</tbody>
</table>

NEW MECHANICAL CALCULATIONS METHODOLOGY CONSIDERING THE EFFECTS OF EXTREME WINDS

At this stage was developed a new methodology for the mechanical calculations of distribution overhead lines considering the results of studies performed to redefine the maximum wind project speed and pressures acting on structures and conductors, in addition, a methodology was included to determine the stresses caused by the high intensity and short duration wind (wind gusts).

A. Discussion about Meteorological Parameters

The definition of project wind speeds was made with emphasis on statistical approach, more realistic and widely used in transmission line projects to replace the deterministic treatment currently used in distribution network projects.

The new methodology proposes that overhead distribution lines must be designed to withstand, without failure, the mechanical loads produced by winds with maximum speeds defined by statistical processing of measurement data of meteorological stations from nearby regions and probabilistic characterization to return period 50, 100, or 150 years.

The variables involved in the definition of project wind speed for the mechanical calculations of conductors and structures are:

- **Return Period**: corresponds to the time estimated that a maximum wind speed is equalled or exceeded at least once, measured in years. The choice of return period (50, 100 or 150 years) to be adopted in the projects of distribution networks direct impacts the reliability level and construction costs.

- **Integration time**: corresponds to the time interval over which the wind speed is calculated. Thus, a 10 minute wind is the average speed in a measurement interval of 10 minutes obtained from an anemograph.

The use of the integration time in the calculations of structures is directly connected to the inertia of the obstacle and its dimensions. For example, a structure such as a pole or a tower, mechanically responds to long term wind (10 minute) and the short gusts (3 seconds) because it has a dimension compatible with the wind wavefront. The cables, which have much smaller size, take longer to respond to the wavefront, therefore efforts for the conductors are used only with 10 minute integration time wind. All these values are parameterized in ABNT [2] and IEC 60826 [3].

B. New Methodology to Calculate the Efforts Due to Wind Considering a Statistical Approach of Meteorological Parameters

In the project of structures, to calculate the mechanical load due to wind action should be considered the two conditions of maximum winds below, being determinant the one with the highest value of mechanical load:

- mechanical loads produced by maximum winds with 10 minutes integration time acting on the structures and cables;
- mechanical loads produced by high intensity winds, with integration time of 3 seconds, performing only on the structures, to represent the gusty winds during storms.

Load Calculation for 10 min winds (maximum wind)

As described above, a wavefront 10 minutes winds acting in an overhead distribution network structure causes horizontal forces in the conductors and poles. The calculations of wind loads on each component will be made according to the following criteria:

a) **Wind pressure - 10 minutes**

\[ q_{10\,min} = \frac{I}{2} \cdot \tau \cdot \mu \cdot v_{p\,10\,min}^2 \]  

- \( q_{10\,min} \) - wind dynamic pressure for 10 minutes (N/m²)
- \( \mu \) - air specific mass (kg/m³)
- \( \tau \) - correction factor of \( \mu \) in function of temperature associated to the maximum wind and altitude
- \( v_{p\,10\,min} \) - 10 minute project wind speed (m/s)

b) **Wind pressure on conductors**

\[ p_{vc} = q_{10\,min} \cdot C_w \cdot G_e \cdot G_L \]  

- \( p_{vc} \) - project wind pressure on conductor (N/m²)
- \( q_{10\,min} \) - dynamic reference pressure for 10 minutes wind (N/m²)
- \( C_w \) - drag coefficient of the conductor, equal to 1.0 for cylindrical elements
- \( G_e \) - combined factor of the wind for conductors, depending on the height and terrain category
- \( G_L \) - gap factor

c) **Wind load on conductors**

\[ H_{c\,10\,min} = p_{vc} \cdot d_c \cdot v_m \]  

- \( H_{c\,10\,min} \) - horizontal load on conductor due to 10 minutes wind (N)
- \( p_{vc} \) - project wind pressure on conductor (N/m²)
- \( d_c \) - conductor diameter (m)
- \( v_m \) - average gap or wind gap structure (m)
d) Wind pressure on pole

\[ p_{wp} = q_{10\min} \cdot C_{wp} \cdot G_t \] (4)

- \( p_{wp} \) – project wind pressure on the pole (N/m²)
- \( q_{10\min} \) – reference dynamic pressure for 10 min wind (N/m²)
- \( C_{wp} \) - drag coefficient of the pole, equal to:
  1.0 for cylindrical elements (circular post)
  2.0 for flat surfaces (rectangular pole)
- \( G_t \) - combined wind factor obtained depending on the height of the center of gravity of the structure relative to the ground.

e) Wind mechanical load on the pole

\[ H_{p 10\min} = p_{wp} \cdot A_p \] (5)

- \( H_{p 10\min} \) – horizontal load on the pole due to 10 minutes wind (N)
- \( p_{wp} \) – project wind pressure on the pole (N/m²)
- \( A_p \) – pole surface area exposed to wind (m²)

Obs.: For the flat poles, 10 minutes wind loading should be calculated on the surface perpendicular to the incident wind direction.

Load calculation for 3 seconds winds (gusts)

The gust of wind stress is caused by localized bursts, ie if they extend to an overhead distribution line, only the post will be affected. The conductors, for having small size, have a low response to dynamic pressure. The calculation of mechanical loads resulting follows:

a) Pressure for 3 seconds winds

\[ q_{3s} = \frac{1}{2} \cdot \mu \cdot v_{p, 3s}^2 \] (6)

- \( q_{3s} \) – reference dynamic wind pressure for 3 sec (N/m²)
- \( \mu \) - air specific mass (kg/m³)
- \( \tau \) - correction factor of \( \mu \) in function of temperature associated to the maximum wind and altitude \( v_{p, 3s} \)–3 seconds project wind speed (m/s)

b) Wind pressure on pole

\[ p_{wp} = q_{3s} \cdot C_{wp} \] (7)

- \( p_{wp} \) – project wind pressure on the pole (N/m²)
- \( q_{3s} \) – reference dynamic pressure for 3 sec (N/m²)
- \( C_{wp} \) - drag coefficient of the pole, equal to:
  1.0 for cylindrical elements (circular post)
  2.0 for flat surfaces (rectangular pole)

c) Wind mechanical load on pole

\[ H_{p 3s} = p_{wp} \cdot A_p \] (8)

- \( H_{p 3s} \) – horizontal load due to wind on the pole (N)
- \( p_{wp} \) – project wind pressure on the pole (N/m²)
- \( A_p \) – pole surface area exposed to wind (m²)

Obs.: For the flat poles, 3 seconds wind loading should be calculated on the surface with greater wind incidence area.

d) Calculation of the resulting wind loads

To calculate the resulting effort must be added the horizontal loads of each component and transferred to 10 cm from the top.

Resulting in the structure due to the wind 10 minutes (maximum wind):

\[ H_{10\min} = H_{c 10\min} + H_{p 10\min} \] (9)

Resulting in the structure due to 3 seconds wind:

\[ H_{3s} = H_{p 3s} \] (10)

To determine the wind load to be considered in the mechanical dimensioning should be adopted which the highest value between \( H_{10\min} \) and \( H_{3s} \).

C. Wind Load Calculation Examples

It can be observed in Table 4 the results of simulations performed to illustrate the use of the proposed methodology to calculate efforts due to wind in rural overhead distribution structures, with distance of 80m between structures. The cable used is a 336,4 MCM and covered conductor (3 x 185 mm2 – Aluminum): Circular section concrete pole (11 m x 300 daN) Rectangular pole (11 m x 300 daN).

Were calculated wind loads for the wind hypothesis with maximum return period of 50, 100 and 150 years on the structure and cables, and the extreme case of wind gust acting only in the structure.

Table 2 – Resulting from wind loads in rural networks

<table>
<thead>
<tr>
<th>Return period (years)</th>
<th>Wind type</th>
<th>Bare conductor</th>
<th>Covered conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind load on poles (daN)</td>
<td>Circular pole</td>
<td>Rectangular pole</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>50 Max. Wind</td>
<td>460.06</td>
<td>----</td>
<td>503,36</td>
</tr>
<tr>
<td>Wind gust</td>
<td>133.02</td>
<td>259.59</td>
<td>196.91</td>
</tr>
<tr>
<td>100 Max. Wind</td>
<td>504.92</td>
<td>----</td>
<td>552.44</td>
</tr>
<tr>
<td>Wind gust</td>
<td>149.13</td>
<td>291.03</td>
<td>220.75</td>
</tr>
<tr>
<td>150 Max. Wind</td>
<td>606.90</td>
<td>----</td>
<td>657.44</td>
</tr>
<tr>
<td>Wind gust</td>
<td>166.16</td>
<td>324.27</td>
<td>245.96</td>
</tr>
</tbody>
</table>

Note: are indicated in bold, loads values that exceed the specified for exceptional load limit of the poles, that are 40% more than the nominal load.

DETERMINATION OF EFFORTS INVOLVED IN TREE FALL ON THE NETWORK

To determine the mechanical stresses in the network due to the impact caused by a falling tree on the cables, were used standard spacer cable structures modeled by the finite element method, a through dynamic transient analysis using ANSYS software LS-Dyna.

A. Network configurations

For the tree fall simulations on compact networks were considered the following networks configurations and tree positions on the post of central span:

- Urban lines (space between structures of 30 m) and tree in the middle of the central span and the 3 m to the pole;
- Rural lines (space between structures of 50 m) and...
B. Comments about model

- The model was considered with linear behavior and was not included any failure criteria for any of the components;
- With the exception of cables, all items of the analysis were considered rigid (* MAT_RIGID);
- To the cylinder representing the tree, the density was adjusted to be equal to the mass of 1.500 kg. A node at the base of the cylinder was set so as to create a bearing allowing tilting of the tree.
- All other hard items were considered fixed

C. Results of tree falls simulations

As an example are presented below the results for one of the cases of simulation performed with rural lines (span of 50 m) and tree falling in the middle of the central span. In Figure 3 is shown schematically the basic configuration of the simulated spacer cable line and in particular the tree fall position.

![Figure 3 – Structures and initial position of the tree on the line](image)

As an example is shown below the effort graph produced in anchorage 1 due to fall from the tree on the messenger cable. For other items and structures is presented only a summary in table form.

Table 3 - Resulting stresses in the anchorage structure 1

<table>
<thead>
<tr>
<th>Effort</th>
<th>Rural</th>
<th>Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hm – Longitudinal on the messenger</td>
<td>-8.372</td>
<td>1.641</td>
</tr>
<tr>
<td>V1 – Vertical on messenger fixing</td>
<td>-220</td>
<td>851</td>
</tr>
<tr>
<td>H1 – Longitudinal – Conductor Fase 1</td>
<td>-2.441</td>
<td>2.524</td>
</tr>
<tr>
<td>H2 – Longitudinal – Conductor Fase 2</td>
<td>-4.225</td>
<td>847</td>
</tr>
<tr>
<td>H3 – Longitudinal – Conductor Fase 3</td>
<td>-13.448</td>
<td>703</td>
</tr>
<tr>
<td>V2 – Vertical in the fixing bracket</td>
<td>-17.534</td>
<td>1.134</td>
</tr>
</tbody>
</table>

b) Passage 1

Table 4 - Resulting stresses in the passage structure 1

<table>
<thead>
<tr>
<th>Effort</th>
<th>Rural</th>
<th>Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 – Longitudinal on the messenger</td>
<td>150.380</td>
<td>8.234</td>
</tr>
<tr>
<td>V1 – Vertical on messenger fixing</td>
<td>-3</td>
<td>19.930</td>
</tr>
<tr>
<td>H3 – Transverse on messenger fixing</td>
<td>-15.553</td>
<td>600</td>
</tr>
</tbody>
</table>

c) Passage 2

Table 5 - Resulting stresses in the passage structure 2

<table>
<thead>
<tr>
<th>Effort</th>
<th>Rural</th>
<th>Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 – Longitudinal on the messenger</td>
<td>-8.309</td>
<td>148.740</td>
</tr>
<tr>
<td>V1 – Vertical on messenger fixing</td>
<td>-1</td>
<td>20.007</td>
</tr>
<tr>
<td>H3 – Transverse on messenger fixing</td>
<td>-15.541</td>
<td>600</td>
</tr>
</tbody>
</table>

d) Anchorage 2

Table 6 - Resulting stresses in the anchorage structure 2

<table>
<thead>
<tr>
<th>Effort</th>
<th>Rural</th>
<th>Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hm – Longitudinal on the messenger</td>
<td>-1.230</td>
<td>8.477</td>
</tr>
<tr>
<td>V1 – Vertical on messenger fixing</td>
<td>-178</td>
<td>843</td>
</tr>
<tr>
<td>H1 – Longitudinal – Conductor Fase 1</td>
<td>-1.794</td>
<td>2.112</td>
</tr>
<tr>
<td>H2 – Longitudinal – Conductor Fase 2</td>
<td>-487</td>
<td>3.747</td>
</tr>
<tr>
<td>H3 – Longitudinal – Conductor Fase 3</td>
<td>-379</td>
<td>12.240</td>
</tr>
<tr>
<td>V2 – Vertical in the fixing bracket</td>
<td>-338</td>
<td>777</td>
</tr>
</tbody>
</table>

D. Discussion about the obtained results

As seen in the presented simulations, the values of the stresses produced by the impact of large tree falling on the spacer cable line make it impossible, technically and economically, the project of structures to support these levels of effort. The recommended alternative to avoid that tree fall impacts and other large objects on the network cause further damage, is to promote the mechanical coordination with the use of mechanical fuse devices, being the least resistance component in the structures and...
projected to operate (break) when subjected to a certain load, before the rupture of cables or poles.

**MECHANICAL FUSES DEFINITION**

To preserve the integrity of the pole, messenger and cables in case of occurrence of events in the distribution lines, such as falling trees and heavy objects, the element or weaker component (mechanical fuse) to be inserted in the structure will break when subjected to a equivalent dynamic effort, with value lower than the pole, messenger cable and conductors nominal rupture load.

**A. Components mechanical characteristics of spacer cable lines**

Find below an analysis of the main types of spacer cable lines structures, to identify the applied loads and the points where can be introduced the mechanical fuse elements.

a) **Structures mechanical protection**

**Passage structure**

![Passage structure diagram](image)

**Anchorage structure**

![Anchorage structure diagram](image)

b) **Concrete pole**

Table 9 shows the poles exceptional loads and rupture loads specified in Brazilian standards, and, in the last column, the values suggested for the rupture of mechanical fuses, considering the objective to break with a force equivalent to 80% of the pole breaking load.

<table>
<thead>
<tr>
<th>Nominal load (daN)</th>
<th>Exceptional load (1.4xRn) (daN)</th>
<th>Rupture load (Rp=2xRn) (daN)</th>
<th>Mechanical fuse (0.8xRp) (daN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>420</td>
<td>600</td>
<td>480</td>
</tr>
<tr>
<td>600</td>
<td>840</td>
<td>1.200</td>
<td>960</td>
</tr>
<tr>
<td>1000</td>
<td>1.400</td>
<td>2.000</td>
<td>1.600</td>
</tr>
<tr>
<td>1200</td>
<td>1.680</td>
<td>2.400</td>
<td>1.920</td>
</tr>
<tr>
<td>1500</td>
<td>2.100</td>
<td>3.000</td>
<td>2.400</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The results of the statistical analysis of weather stations measurements data allowed obtaining, for the Celesc concession area, a mapping occurrence of winds with maximum speeds expected with probabilistic characterization of occurrence. What enabled revise the current mechanical structures calculation methodology for overhead distribution networks, according to the characteristics of each region and probabilistic characterization to return period (50, 100 or 150 years), including efforts due to high intensity bursts and short duration winds.

The results of studies to estimate the mechanical forces acting on conductors and structures, when trees falls onto the conductors, through simulations by finite element method, indicated the need for the use of mechanical fuses to minimize the risk of cables and poles rupture in the case of falling trees or heavier objects on the overhead distribution line.

The results of these studies allowed Celesc to develop new standards on overhead networks, mechanically coordinates, which are being subjected to field trials (experimental lines).

**REFERENCES**

