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Computer-based mechanical design of overhead lines

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Abstract. Beside the performance, the safety level according to the actual standards is a compulsory condition for distribution grids’ operation. Some of the measures leading to improvement of the overhead lines reliability ask for installations’ modernization. The constraints imposed to the new lines components refer to the technical aspects as thermal stress or voltage drop, and look for economic efficiency, too. The mechanical sizing of the overhead lines is after all an optimization problem. More precisely, the task in designing of the overhead line profile is to size poles, cross-arms and stays and locate poles along a line route so that the total costs of the line’s structure to be minimized and the technical and safety constraints to be fulfilled.

The authors present in this paper an application for the Computer-Based Mechanical Design of the Overhead Lines and the features of the corresponding Visual Basic program, adjusted to the distribution lines. The constraints of the optimization problem are adjusted to the existing weather and loading conditions of Romania. The outputs of the software application for mechanical design of overhead lines are: the list of components chosen for the line: poles, cross-arms, stays; the list of conductor tension and forces for each pole, cross-arm and stay for different weather conditions; the line profile drawings.

The main features of the mechanical overhead lines design software are interactivity, local optimization function and high-level user-interface.

1. Introduction

In the case of the overhead lines, the absence of further insulation beside the small sections connected on the line supports, as well as the relatively facile construction lead to a low-expensive electric circuit compared to an underground cable, mostly at medium and high voltage levels. While in normal environmental conditions the ratio of underground cable to overhead line costs is within 25:1 to 5:1, in areas of difficult terrain, there is an even bigger cost advantage with overhead lines. In the more sparsely populated areas, the overhead lines routes are more opportune. On the other hand, the majority of the very/high voltage routes are predominantly overhead, also because of the large cost difference to the cables.

Overhead conductors must be installed at a height providing an adequate electrical clearance from the ground, from nearby buildings or vegetation, and over roads and railways. The domain regulations set out the minimum clearance allowing for factors as the swing of conductors in prescribed windy conditions. The line height is determined by the maximum conductor sag between towers. This one is influenced by the span length, the conductor type, the maximum permissible conductor stress, the maximum conductor temperature, and the air ambient temperature. Calculation of overhead lines mechanics should take into account all the above criteria [1-3].
In general, the overhead conductor elongates by the permanent mechanical forces during its lifetime. Additional to this irreversible elongation, the sag of overhead conductors will increase with temperature caused by the electrical load and specific environmental conditions or other rope forces, e.g. snow and ice load. During the planning and construction, a lower sag than necessary gives a safety distance to the regulation clearance. With sag design or verification of planned or aged overhead lines by measurement or calculation, the reliability of the overhead lines can be improved. Depending on the system voltage and object type, the minimum phase to earth clearance can be ensured, too.

2. The design objective
In general, the design of the overhead lines has the following steps [1], [2], [4]:

1. input data collecting
2. route selection
3. conductor type selection
4. poles type selection
5. setting of the basic span length
6. pole positions nomination
7. choosing of tower heights and circuit heights at supports
8. drawing of ground line profile
9. drawing of circuit profile
10. checking of the vertical and horizontal clearance
11. checking of the structure stability to the mechanical forces
12. other requirements.

Some other initial conditions can be initially assumed as for instance, the poles height and size. These ones may later need to be amended as the design is checked and gradually refined. More options will be tried iteratively until an optimum arrangement is obtained.

The input data required by the profiling overhead algorithm should be organized in an appropriate shape file including all relevant requirements, constraints and background information as the following: existing and proposed schematics; planning requirements; future development; authorities requirements; coordination with lighting system; maps.

The design purpose is optimizing the profile of an overhead line by minimizing the line construction costs. The algorithm is adjusted for a software implementation allowing to the designer to find a first constructive solution.

The procedure for profiling the overhead lines firstly considers information about ground level coordinates of the line routes and superimposes the pole positions on the ground profile and their dimensions. Based on this information, the computer-based algorithm calculates the sag curves and draws the line profile under different weather conditions, e.g. minimum temperature of \(-30^\circ\text{C}\) (without wind and ice), maximum temperature of \(+40^\circ\text{C}\), medium temperatures \((+15^\circ\text{C}, +20^\circ\text{C}, +30^\circ\text{C})\) without/with wind, ice load conditions at \(-5^\circ\text{C}\) without wind or with windy condition.

The sag template for drawing the circuit profile is established taking into account the permanent and the variable loading conditions. The profile is checked to ensure that:

- the circuit profile does not cross beyond the ground line offset line;
- adequate clearance is kept between neighborhood circuits or relative to other structures.

In case the ground clearance is not fulfilled, the program considers to increase the pole height or to reduce the span length by introducing supplementary poles so that the cost of line construction is minimized.

The constraints of the minimization problem are:

- the horizontal tension on the conductor should be less than a maximum allowable value, fulfilled for the distance between two poles less than the critical span of the conductor;
- there must be fulfilled the national safety regulations (clearance);
- the line route often has areas where the pole location is forbidden.
3. The design program structure

The software program entitled *Mechanical design of overhead lines* (in Romanian), is a Visual Basic application, with a friendly interface and Excel and Mathcad export/import facilities. The software is designated to profile the distribution overhead lines fulfilling the clearance restrictions and to obtain a minimization of the line construction by a proper selection of the poles position and heights [5]. There should be mentioned this version of the design program does not have global optimization algorithm for pole location. The main structure of the overhead line profiling software is given in Figure 1, and its modules are described as following:

I. Firstly, the ground line profile is plotted at a convenient scale (e.g. 1:1000) using the survey data for the line route profile. The survey data consists of distance and slope information for constitutive ground segments, between which the ground is considered with constant slope. A pair of trigonometric formulae is used in this stage:

\[ x_{i+1} = x_i + d_i \cdot \cos \theta_i; \quad y_{i+1} = y_i + d_i \cdot \sin \theta_i, \]  

(1)

Where, \( x_{i+1}, x_i \) is the horizontal coordinate at the \( i-th \) ground segment end, respectively ground segment start, [m], \( y_{i+1}, y_i \) is the vertical height at the \( i-th \) ground segment end, respectively ground segment start, [m], \( d_i \) is the measured length of the \( i-th \) ground segment, [m] and \( \theta_i \) is the slope of the \( i-th \) ground segment, [deg].

Figure 1. Algorithm structure for profiling of overhead lines

II. The coordinates are set for superimposed initial locations of the poles on the line route, for certain type of poles. In this stage, the same height is considered for all poles (e.g. 16 m).
III. There are also introduced the clearance requirements and weather conditions, as well as pole costs expressed in monetary values on height unit.

IV. The line route is considered as divided in segments for which the equivalent span is calculated, according to the following steps:

IV.1. The conductor loadings for different weather conditions, \( g_k \) [daN/m mm\(^2\)], are determined;

IV.2. The tensions of the conductor under corresponding weather conditions are determined iteratively, using a Newton-Raphson algorithm applied to the state equation (2), given as in [3], [4], [6]:

\[
\sigma_n - \frac{B_n}{\sigma_n^2} = A
\]  

where \( \sigma_n \) is the conductor tension for the considered weather condition (n-named), [daN/mm\(^2\)], \( B_n \) is coefficient of state equation variable for weather condition \( n \), given by the equation (3) and \( A \) is free term of the state equation given by the equation (4):

\[
B_n = a^2 g_k^2 \cdot E / 24,
\]  

where \( a \) is the span of the tension line segment, [m], \( g_k \) is the conductor loadings for \( k \) weather condition, [daN/m·mm\(^2\)], according to [3] and \( E \) is elastic coefficient of the conductor, [daN/mm\(^2\)],

\[
A = \sigma_{ref} - \frac{B_{ref}}{\sigma_{ref}^2} - E \cdot \alpha \cdot (\theta_n - \theta_{ref})
\]  

where \( \sigma_{ref} \) is the conductor tension for the reference weather conditions, [daN/mm\(^2\)], \( B_{ref} \) is coefficient of state equation variable for reference weather condition, given by the equation (3), \( \alpha \) is temperature coefficient of the conductor, [\(^{\circ}\)C\(^{-1}\)] and \( \theta_n, \theta_{ref} \) is temperatures of conditions \( n \), respectively reference, [\(^{\circ}\)C].

IV.3. Using a parabolic function, the sag curve (5) for support at different level is determined:

\[
f(x) = 4 \cdot f \cdot x / a \cdot (1 - x / a).
\]  

Where, \( f \) is the curve sag, [m].

\[
f = \frac{a^2 \cdot g}{8 \cdot \sigma}
\]  

IV.4. The maximum span length is determined:

\[
a_{cr} = \frac{\sigma_{max,adm} \cdot \sqrt{24(\theta_{5^\circ} - \theta_{min})}}{\left( \frac{g_{cond,ice}}{\sigma_{Al-5^\circC+ice}} \right)^2 - \left( \frac{g_{cond}}{\sigma_{Al,min}} \right)^2}, [m].
\]  

where, \( \theta_{min} \) is the minimum temperature (-30\(^{\circ}\)C), \( g_{cond} \) \( g_{cond,ice} \) is loadings of the conductor under its own weight, respectively with ice weight and \( \sigma_{Al-5^\circC+ice} \), \( \sigma_{Al,min} \) is aluminium conductor tensions for \(-5^\circ C + ice \) condition, respectively minimum temperature, according [3].

V. The poles position is changed on those segments where the critical span length is exceeded.

VI. The line route is plotted and the ground clearance is checked.

VII. The line construction costs are determined.

VIII. The pole height is reduced at those segments where the ground clearance is allowing.

IX. The new line construction costs are determined.
4. The model simulation results

The software application outputs consist in the following data:
- list of poles chosen for line construction and their costs;
- list of conductor tensions for different weather conditions;
- list of span lengths for the ground profile segments;
- list of sags for ground profile segments for different weather conditions;
- drawing of the ground profile (by constitutive segments);
- drawing of the line profile for different weather conditions.

The program *Mechanical design of overhead lines* has a high level of interactivity given by an intuitive graphic interface. Figure 2 shows the screen shot indicating the resulting equivalent tension of a sample conductor for different weather conditions, while in Figure 3 one of the final screen shots of the application is shown.

![Figure 2. Screen shot with equivalent tensions on the conductor](image)

![Figure 3. Screen shot of *Mechanical design of overhead lines* with segment line sag values](image)
The output data lists are also organized in Excel reports containing the values generated in different stages of line mechanical calculus.

Figure 4 shows a sample of the sag curve generated by software for two constitutive segments of the conductor profile and the ground clearance curve. If there is no intersection between these two curves, the ground clearance requirements are fulfilled.

![Figure 4. Software line profile output](image)

5. Conclusions
The software Mechanical design of overhead lines is an efficient tool for profiling of overhead distributions lines.

The design software application includes modules for calculus of line tensions, line sag curves, graphical outputs of ground and line profiles, as well as an iterative algorithm for minimization of poles heights with fulfilling of clearance restrictions.

By using such of designing tool, the overhead lines sizing can become more accurate, and consequently, more costly efficient. The designing time can be sensible reduced and the interactivity features can by more supportive for designers.

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