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Analyses of the overhead-line cable stringing and sagging on hilly terrain with an absolute nodal coordinate formulation

Borut Zemljarič*

Design Engineering Department, Elektro Gorenjska, Kranj, Slovenia

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ABSTRACT

The method of absolute nodal coordinate formulation (ANCF) is used to solve the problem of determining the cable sags and the forces during the cable stringing and sagging process for overhead lines. The problem of calculating the sagging tables due to the temporary supporting cable sheave deflection during the construction phase is emphasized on hilly terrain. Two different models for the contact point between the cable and the sheave are analyzed. The most important advantage of this newly proposed approach is that it opens up the possibilities for analyzing more complex overhead-line structures that are a consequence of the line compaction, e.g., using unconventional insulating applications. The paper describes the basic steps of an ANCF algorithm to solve the presented problem. It also provides numerical examples in order to verify the ANCF method by comparing it with the results of other known approaches based on catenary equations.

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1. Introduction

This paper deals with the problem of determining the cable's sags, the forces and the insulator offset clipping during the cable's stringing and the final sagging process for overhead, high-voltage, transmission power lines. The problem occurs during the cable's installation phase on the overhead-line towers when new overhead lines are under construction, during the replacement of a cable as part of an overhead-line refurbishment or during an upgrade of existing overhead lines with new conductors. The stringing is understood as cable pulling, while the sagging is the final sag adjustment with respect to the predicted conductor sag values. The word cable is used in this paper to describe a bare or insulated conductor. The mechanical behavior of cables suspended on free-to-roll sheaves that are temporarily hanging on suspenders, where insulators are normally used as suspenders, differs significantly from the behavior of cables that are fixed on suspension clamps. As a consequence, during sagging the insulators are not in a vertical position, as we want them to be, and the individual cable span sags and the corresponding cable forces do not comply with the final sags and forces that are predicted during the line planning with respect to the installation sagging tables. The new design concepts in high-voltage transmission lines with the introduction of compact overhead lines with rotating post line insulators, special insulator systems, the stringing and sagging of long cable lengths over multi-tension fields, as well as using higher-voltage levels with an increased number of cables in the bundle, these days force us to upgrade our knowledge about the cable stringing and sagging on overhead transmission lines.

Today, the approach to the problem's solution and the corresponding software tools tend, in most cases, to follow the method elaborated by Kiesling et al. [1]. This method uses classic catenary equations for the cable state and the sheave is presented as a mass point for the insulator as a suspender. The model takes into account that the cable length in the tension field is the same, when the cable rests on the sheaves or it is clipped in the end of the insulator. After finding, by iteration, the values of the individual span's horizontal tensions and the sheave's suspender deflection angles, which change the initial spans and the height differences, finally, new temporary sagging tables are calculated and used during the cable-stringing process. No cable bending is included in the model.

McDonald and Peyrot [2] presented the pulley-element concept as a supplement to the cable-element concept [3], with which, using the classic finite-element method, the presented problem can also be analyzed. The pulley element is like the black-box finite element, and is limited to classic sheave and hanging-insulator applications.

This paper introduces the method of the absolute nodal coordinate formulation (ANCF) into overhead-line design calculations in order to analyze and solve these challenges. Shabana [4] introduced the ANCF to be used in the analyses of large multibody rotations and deformations, as one of the finite-element methods.

* Tel.: +38 631574995.
E-mail address: borut.zemljaric@siol.net

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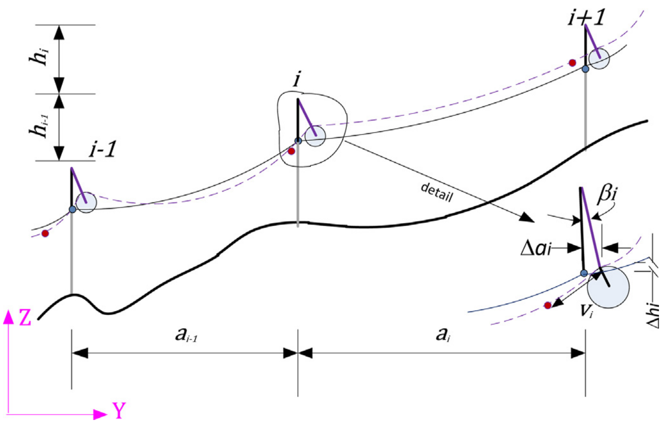

Fig. 1. Overhead-line profile in the final (continuous line) and the stringing (dashed line) states.

Based on continuum mechanics, the ANCF method is a consistent mathematical method. In the ANCF the nodal coordinates and slopes are defined in the global coordinate system, which is very convenient from the point of view of overhead-line designers. Another great advantage of this method is that it is open to an arbitrary system geometry, it takes the cable bending stiffness into account in the model, and if necessary it can be upgraded with more details regarding the cable and sheave friction as well as being easily expanded and used to study dynamic problems. As a dynamic problem example, it is important to mention the calculation of the dynamic forces in a system when the pilot rope or cable is strung with a non-pilot, multi-copter, flying device or helicopter.

This paper is organized as follows. After the introduction, a brief review of the problem's background is given in Section 2. Section 3 outlines the basics of the ANCF method and describes the concept of the cable, insulators and sheaves together as a sheave system in a multibody mechanical system. In this section the mechanical constraints used in the ANCF are introduced for the problem at hand. The two different mechanical types simulating the sheave system are given, i.e., the slide joint and the contact joint. The next section, Section 4, gives the numerical examples. Finally, the conclusions are drawn.

2. Problem background

Let us consider that the overhead-line tension field consists of n spans with an individual span length a_i, as presented in Fig. 1. The behavior of the cables fixed to the suspension clamps is the desired state and is drawn with a continuous line. The desired state differs from the one during installation, when the cables are lying on the sheaves; it is drawn with a dashed line in Fig. 1. Regarding the suspenders rotation angle β_i, the span lengths a_i and the desired span height differences h_i differ by the values Δa_i and Δh_i, and the horizontal forces F_{Hi-1} and F_{Hi} in the adjacent spans are different when the cable lies on the sheaves. In the fixed clamp, the position of the vertical insulator is only achieved if the cable's horizontal forces are equal for all the spans.

The reasons for these differences in the horizontal force on rough hilly terrain are the existence of large vertical differences between the cable attachment points on the towers, or on flat terrain the large span differences between the suspension towers. The larger are the height or span differences, the more emphasized are the insulator deflections from the vertical position and the actual span length during cable stringing from the desired, design span lengths. For a cable lying on sheaves, the forces on the cable change with the slope of the terrain. So that at the beginning of the terrain slope they are smaller and at the end of the slope they are higher. The sags act in the opposite sense to the cable forces. In the spans where the slope starts they are higher than for the upwards ones. Generally speaking, insulators tend to move upwards with respect to the terrain slope. The presented conclusions are valid for the cables lying on sheaves in the stringing of the overhead-line installation phase. In order to obtain the final design sags and ensure the required position of the insulators is met, before permanent clipping into the hanging cable clamps, the clamp position adjustment, called the clipping offset, regarding the cable's attachment point to the sheave's suspension position, must be made. Knowing the clipping offset length v_i, which is the distance between the cable contact point with the sheave and the point where the fixed clamp should be placed (full dot), Fig. 1, the horizontal forces are mutually compensated, equalizing the horizontal cable's tension force for all the spans inside the tension field.

The goal of the presented ANFC procedure, which will follow, is to (1) calculate the cable forces in all the individual spans, (2) the offset clipping distances between the final positions of the clamp and the sheave's supporting point for the cable resting on the sheaves and (3) the corresponding sheave-suspender (insulator) deflection angles from the desired positions. After the cable sagging, by fixing the clamp to the calculated offset clipping point, the sags and the insulator strings will automatically take up the desired design position. Also, if necessary, based on the calculation results, additional information can be extracted. For example, when the cable length in the stringing process covers more than one overhead-line tension field. In that case, during the cable stringing, the horizontal force at the end tension tower with the highest ground altitude can significantly exceed the final designed horizontal tension, which will be met later in the installation process, after the final cable clipping.

The problem determination for the position of the cables on overhead lines during sagging, from the point of view of the ANCF method, is only a special case of the ANCF method, as we are only performing static analyses. For simplicity and comparability between the methods, the problem-solving is presented for a two-dimensional case. However, expansion to a three-dimensional ANCF method is straightforward.

3. ANCF method

The ANCF method, like other finite-element methods, requires a determination of the initial system state, which is based on finite elements. The first task is to disassemble the overhead line into finite elements. The cable is segmented into an arbitrary number of elements per span, and the suspender (insulator) and the sheave are modeled in a finite-element manner, as follows.

3.1. Cable element and generalized cable-element forces

In this paper, two-dimensional cable elements are used. As stated previously, the unstrained cable length for a given span L_i, $i = 1\ldots n$ is divided by an arbitrary number of chosen elements per span $j = 1\ldots n_e$ into the initial unstrained element lengths L_{ij}. As shown in [5] for the cable element, only one position vector and only one gradient vector are used as the absolute coordinates for each node. Fig. 2 shows the cable element in the initial and deformed configurations. The normalized parameter is determined as $\xi = x/L_{ij}$, where x is the undeformed parameter's dimensional length. The position gradients are excluded in the cable element. Using this simplification it is possible to model the axial cable bending, but the torsional effects cannot be considered. Therefore, the cable element cross-section remains plane and perpendicular to the center line of the cable. In the case of overhead cables, the span length is much larger than the cable diameter; consequently, the

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