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INTRODUCTION TO ACSR CONDUCTOR SAG AT HIGH TEMPERATURE

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SUMMARY

Maintaining clearances between an overhead line transmission conductor and grounded objects over the lifetime of a transmission line is an important criterion to be considered in the design and operation of the transmission line. Sufficient clearances between the overhead line conductor and objects on the ground is critical for the safe and reliable operation of the transmission line.

Clearances between the conductor and ground is directly related to the sag of the transmission line. One factor which governs the sag of the conductor is the temperature at which the conductor operates. As many transmission lines are now being operated at higher temperature, which results in more sag, an accurate method of determining conductor sag becomes more important. Conductor sag is typically calculated using a catenary equation which takes into account the span length and conductor tension. Temperature sag changes are accounted for by using an iterative process which includes calculating the expansion of the material which makes up the conductor.

In a bimetallic conductor such as Aluminum Conductor Steel Reinforced (ACSR), the sag of the conductor is initially governed by both the outer (aluminum) and inner (steel strands). At a certain point the tension applied on the conductor is maintained solely by the steel core as the aluminum strands expand and unload the tension onto the core strands. From this point onward the conductor sag is governed by the steel core – this is known as the knee-point of the conductor sag curve. Over the years, various laboratory and field tests have indicated that the sag of ACSR conductors above the knee-point is not consistent and therefore not clearly understood. In some of these tests, more sag was measured than what was predicted by the traditional sag models predicted. Different hypothesis have been put forward to explain the extra sag measured during these high temperature tests.

The traditional models typically employed to determine conductor sags are: (i.) The Linear Elongation (LE) Model; (ii.) The Simplified Plastic Elongation (SPE) Model, and (iii.) The Experimental Plastic Elongation (EPE) Model. These models have been shown to

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inaccurately predict the conductor sag when the conductor surface temperature exceeds the knee point temperature. Other models (variations of the EPE Model) which have been proposed to describe ACSR conductor sag at high temperatures take into account factors such as the conductor manufacturing process and the effect of aluminum strand compression.

This paper discusses the traditional models used for determining the mechanical behavior of ACSR conductors and the errors associated with each of these models, and the factors which can influence conductor sag. An analysis is carried on the models proposed by Rawlins and Barrett, [9, 10] which describe the conductor sag at higher temperatures. A review of the various high temperature field and laboratory tests and results which have been published detailing the sag measured at temperatures above the knee-point temperature will also be discussed and finally tests to verify specific conductor parameters (such as the compression of the aluminum outer strands) which could influence the conductor sag behavior will be proposed.

KEYWORDS

Transmission Line, Catenary, Sag-Tension, Knee-Point, Aluminum Compression, Mill Effects.

INTRODUCTION

Maintaining clearances between an overhead line transmission conductor and grounded objects over the lifetime of a transmission line is an important criterion to be considered in the design and operation of the transmission line. Sufficient clearances between the overhead line conductor and objects on the ground is critical for the safe and reliable operation of the transmission line. The transmission line designer has to ensure that minimum clearances are maintained for the life of the transmission line under both normal and emergency operating conditions.

When designing a new transmission line (or modifying an existing line) the line designer would typically model the conductor in a software program, or by using sag and tension charts for the specific conductor being used. The software program and the sag and tension chart makes use of specific sag and tension data which has been developed for the particular conductor. The line designer would then be able to determine how much strain (elongation of the conductor) would occur for a giving stress (conductor tension). The models used would also take the conductor metallurgical creep into account. A conductor under a specific tension would tend to increase in length (creep) over time. The sag-tension calculations are done in order to predict the conductor sag and tension under various conditions both thermal and mechanical. The mechanical and electrical integrity of the overhead transmission line is dependent on the accuracy of the sag-tension calculations.

CONDUCTOR CATENARY CURVE

The shape of an overhead transmission line connected between points can be described by what is known as a catenary. The catenary is formed by the weight of the conductor and can be accurately modeled using a hyperbolic cosine function, which in Cartesian coordinates is generally as follows: $y = \cosh x$. The generalized form of the catenary curve used to describe a transmission line is as follows: $y = a \cosh \frac{x}{a}$ [1]

Factors which influence the shape of the catenary curve include the weight of the conductor per unit length, **w**, the horizontal component of tension, **H**, the sag of the conductor, **D** and the span length (length between attachment points), **S** [2]. If the two connection points of the conductor are level (the same height) then the lowest point of the catenary formed by the conductor between the points is exactly half the distance between the two attachment points. The equation used to describe a level transmission line catenary relative to its low point is as follows: $y = a\cosh\left(\frac{x}{a} - 1\right)$ [3]. Where a = H/w. Figure 1 below shows the catenary curve of a level span, where **L** is the total length of the conductor in the span.

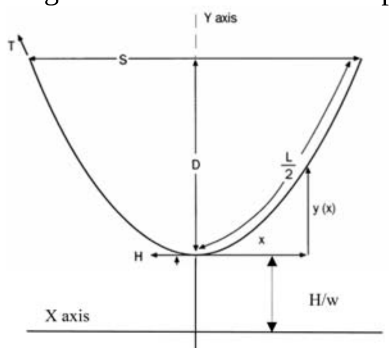

Figure 1: Catenary Curve of a Level Span [2]

The catenary equation for a conductor between two fixed points is expressed in terms of the horizontal distance, x, from the low point of the catenary to a point on the catenary which is y(x) above the vertex. The equation is as follows:

$$y(x) = \frac{H}{w} \cdot \left[\cosh\left(\frac{w \cdot x}{H}\right) - 1\right]$$

The catenary curve can be approximated using a parabolic function which is found by the special Taylor series expansion [4] (known as the Maclaurin expansion) of the hyperbolic cosine function.

$$y(x) \cong \frac{w \cdot x^2}{2 \cdot H}$$

The difference between a catenary curve and a parabolic curve is as follows - In a catenary curve the distribution of weight is uniform per arc length, this is different to a parabolic curve where the distribution of weight is uniform per horizontal unit of length [5].

For a level span the maximum sag (D) occurs at the point S/2. Substituting x = S/2 into the parabolic approximation yields:

$$D \cong \frac{w \cdot S^2}{8 \cdot H}$$

The conductor sag is affected by the conductor's operating temperature. Generally a higher the conductor temperature results in an increase in the depth of the catenary curve, i.e. more sag. This is due to the decrease in the horizontal tension, H.

MODELING CONDUCTOR ELONGATION

When the conductor is installed in the field, the conductor tension or sag is measured with the conductor at a known temperature. The calculation of the sag and tension of the conductor under various mechanical and electrical loading conditions and at various times is dependent on knowing how the conductor responds to [2]:

- Conductor temperature changes
- Ice and wind loading and
- Plastic elongation of the aluminum layers over time

The factors listed above need to be accurately modelled in order to accurately calculate the sag under various conditions. These elongation models can then be used to determine the conductor tension and sag.

CIGRE has classified the different sag tension calculation methods into three distinct approaches [2].

- **The Linear Elastic (LE) Model [6]**
  In this model the conductors are modeled as linear springs with a single coefficient of thermal elongation (CTE) and a single elastic modulus.

- **The Simplified Plastic Elongation (SPE) Model [6]**
  In this model, the conductors are also modeled as linear springs, plastic conductor elongation is accounted for by adding a permanent increase in length (expressed as an equivalent temperature change). The plastic elongation length chosen is based on engineering experience.

  For non-homogeneous conductors such as ACSR the tensions in the aluminum layers and steel core can be calculated for typical plastic elongation, but not for the variation in design loading. A knee-point temperature can be calculated for high conductor temperatures but a dependence on conductor type, span length and design load cannot be calculated.

- **The Experimental Plastic Elongation (EPE) Model (Graphical Method) [7]**
  Overhead conductors are modeled as non-linear springs that elongate elastically as a function of tension, plastically as a function of tension and time and thermally as a function of temperature. For ASCR conductors the non-linearity of the steel core and aluminum layers are modeled separately and the elongation of the steel and aluminum is calculated separately as well. The plastic elongation due to settling of the conductor, metallurgical creep as well as permanent elongation due to high mechanical loads is calculated by assuming a series of loading events over the life of the line. This is the method most commonly used in North America.

CONDUCTOR THERMAL ELONGATION

Conductor length changes as the result of plastic and elastic elongation and due to thermal elongation. Elastic elongation and thermal elongation are reversible (returning to the initial tension and temperature yields the initial length). Thermal elongation is the result of variations in air temperature, solar heating, and line current.

For bare overhead conductors that are stranded with one or more layers of aluminium wires surrounding a steel (or composite) core, the conductor's CTE can be calculated on the basis of the CTE and Elastic Modulus (E) of aluminium and the core material and their relative cross sectional areas.

$$E_{AC} = E_A \cdot \frac{A_A}{A_{AC}} + E_C \cdot \frac{A_C}{A_{AC}}$$

$$CTE_{AC} = CTE_A * \left(\frac{E_A}{E_{AC}} \right) * \left(\frac{A_A}{A_{AC}} \right) + CTE_C * \left(\frac{E_C}{E_{AC}} \right) * \left(\frac{A_C}{A_{AC}} \right)$$

Where the subscripts A refers to Aluminum, C refers to the Core, and AC refers to the complete conductor.

Note that for most ACSR conductors, the composite CTE is closer to aluminum than to steel. For 26/7 ACSR, the composite CTE is 18.8 whereas the aluminum CTE is 23 and the steel core CTE is 11.5.

ACSR CONDUCTOR SAG AT HIGH TEMPERATURES

The sag-tension behavior of ACSR conductors is generally well understood and defined for moderate temperatures (up to about 75 ^{o}C) [8]. However at higher operating temperatures especially with non-homogenous stranded conductors such as ACSR, that the relationship between conductor temperature and sag-tension is not completely understood.

The sources of errors in high temperature sag-tension calculations can be categorized into those which affects the calculations for [8]:

- All types of conductors in a single or multiple span line section
- Conductors in multiple suspension-span line sections
- Non-homogeneous conductors such as ACSR

Factors Affecting High Temperature Sag-Tension Calculations

There are several factors which can impact the accuracy of high-temperature sag calculations for all types of conductors. These factors are as follows.

- Temperature differences between the strands
- Effect of temperature on the elastic modulus and coefficient of thermal expansion
- Creep elongation and increased tension at high temperatures

Factors Affecting Multiple Suspension Span Sag-Tension Calculations

In general the ruling span concept is used to determine the sags of individual spans in line sections. The IEEE report showed that using the ruling span concept could cause sag errors of up to 1 m at 100 ^{o}C.

Factors Affecting the Sag Calculations of Knee-Point" Temperature for ACSR Conductors

The numerical method and the graphical method for sag calculations assumes that there is a knee-point temperature, above which the stress of the aluminum wires is zero. Below this temperature the conductor sag depends on the composite elastic modulus (Steel and aluminum) and composite coefficient of thermal expansion while above this temperature the sag behavior is only dependent on the elastic modulus and coefficient of thermal expansion of the steel only. Studies have shown:

- The knee-point temperature is not an exact temperature. There is a range of about 10-20°C, within which the conductor properties change.

- The coefficient of thermal expansion and modulus of elasticity may differ from theoretical values.
- The knee-point temperature is generally higher than assumed by classical calculation methods. There are two main explanations for this knee-point shift [9, 10] – both will be discussed in this paper.

ACSR CONDUCTOR KNEE-POINT SHIFT AT HIGH TEMPERATURES

The knee-point temperature for ACSR conductors is generally higher than predicted by classical calculation methods. Two main hypothesis have been put forward to explain this knee-point shift.

- Aluminum strand compressive forces – proposed by Barrett
- Effects of conductor manufacturing processes – proposed by Rawlins

Aluminum Strand Compressive Forces

The 1981 paper titled "Characteristics of ACSR Conductor at High Temperatures" [9], details the results of both stress-strain and thermal elongation tests done at Ontario Hydro's research facility in Ontario. Excessive sag measured in high temperature tests of ACSR conductors was explained as being a result of compressive forces which were developed in the conductor. The compressive forces were said to develop in the aluminium strands due to radial temperature gradients between the inner and outer strands. Typically the inner strands would be at a higher temperature than the outer strands (and therefore the outer strands would be at a higher tension loading than the inner strands). The inner strands would then expand but would be physically constrained by the outer aluminium strands. This would cause the bird caging temperature to increase and therefore would lead to increased sag. The constraint of the inner strands would lead to extra loading on the steel core as the inner strands try to expand while being radially constrained, which would result in more sag. The compressive forces due to the constrained aluminium strands in an ACSR conductor were said to be in the region of 6 MPa to 12 MPa, although under specific conditions this could increase to 18 MPa. This compressive force could lead to an increase of 1.5m in sag for a typical 300 m span [9]. Figure 2 shows the measured sag compared to the predicted sag with no bird caging and with no aluminium compression.

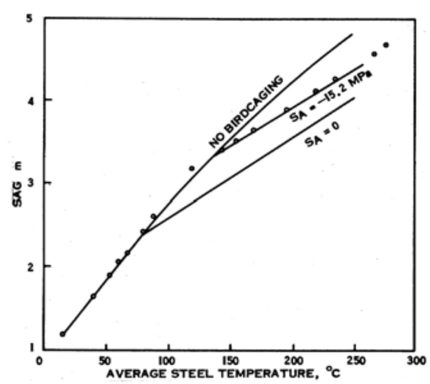

Figure 2: Measured Sag in a 122 m outdoor test span [9]

In figure 2, the curve depicted as SA = 0, is the classic sag calculation curve using the Experimental Plastic Elongation Model. At the knee-point of around 80°C, the increase in sag decreases as the sag is dictated by the characteristics of the steel core from this point onwards. At temperatures below 80°C the sag is dictated by both the steel and aluminium characteristics. This method would result in a lower sag being calculated than what was actually measured.

The curve depicted by “No Bird caging” is the sag calculated using the Linear Elastic Model, the coefficient of thermal expansion is uniform for all conductor temperatures. As can be seen from figure 2, this will lead to excessive sags being calculated which are higher than that actually measured. The actual sag measured in the tests was most accurately modelled by using the EPE model and adding aluminium compression of about 15.2 MPa.

<u>Conductor Manufacturing Processes</u>

In 1999 Charles Rawlins authored a paper titled “Some Effects of Mill Practice on the Stress Strain Behavior of ACSR” [10]. In this paper, he describes two factors which could lead to higher than predicted conductor sag levels.

The first factor discussed by Rawlins is the Built-In Stress in Aluminum of ACSR. This stress according to Rawlins was due to the braking tension on the aluminum wires as they are pulled from their spools in the strander to firm the cable as well as the friction experienced in moving to and through the closing die. The paper indicates that there is considerable variation in estimating the values due to built-in stresses and concluded that due to the limited amount of information available and the large amount of data required to do the analysis, that it was probably nor feasible for the effects of the built in stresses to be evaluated.

The second factor discussed in detail is the Compression Modulus of the Aluminum Part of ACSR. In this section Rawlins evaluates the compression of the aluminium strands according to the proposal made by Barrett in his 1981 paper [9]. Rawlins indicated that his investigation led to lower values of compression than that reported by Barrett. In addition to this, Rawlins developed equations to determine the compressive forces due to the aluminium strand layers interacting with each other.

He concluded that many ACSR conductors do not experience significant aluminium compressive forces as their two outer layers generally conform to the ASTM preferred lay criterion [11]. If the outer lays deviated from the preferred ASTM ratios then the compression force due to the strands interacting with each other becomes significant. Appendix 2 of [10] goes into significant detail on how to calculate the compressive force as a result of the conductor stranding ratios.

Figure 3 shows the results of indoor tests done by the Electric Power Research Institute [12]. The measured sag was compared to the calculated sag levels with several corrections. The sag based on measured conductor tension was the closest match to the actual measured sag in the span. The next closest curve was for the curve which had the calculated sag with corrections for initial tension temperature, built in stresses, aluminium compressive forces and the effect of temperature on elastic moduli.

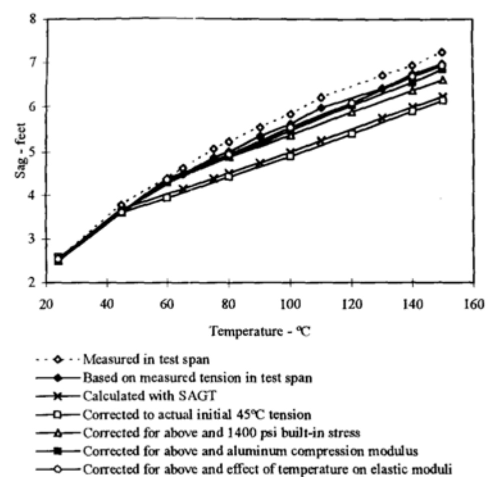

Figure 3: Measured and Predicted Sag Values from EPRI Tests [10]

In an exhaustive discussion of the paper, the main point arising was that it would be very difficult for transmission line designers to accurately predict the sag of existing ACSR transmission lines due to not knowing the built-in stresses and the aluminium compressive forces.

PROPOSED STUDY TO DETERMINE ALUMINUM COMPRESSIVE FORCES

To better understand the behaviour of ACSR conductors at temperatures beyond the knee-point it is proposed that the Barrett and Rawlins models be analysed. Since it will be quite difficult to quantify the mill effects introduced into stranded ACSR conductors as postulated by Rawlins, the analysis will focus on determining the effect of the aluminium stranding on its mechanical performance beyond the knee point temperature. The analysis will be complemented by a numerical parametric evaluation and physical tests to determine the amount of compression which the aluminium strands of an ACSR conductor can withstand before bird caging occurs. The results of the proposed study will improve the understanding of the effects conductor stranding on the sag behaviour of ACSR lines.

CONCLUDING REMARKS

The sag of ACSR conductors at high temperatures is not properly understood. There is a risk of uncertainty in determining the sag these conductors at temperatures exceeding the knee-point. The models proposed both indicate that more sag than what is typically calculated may occur. With the possibility of increased sag, utilities need to perform accurate calculations (taking the conductor strands into account) or make allowance for this. The aim of the proposed study is to provide a better understanding of the conductor behaviour at high temperatures and thereby provide utilities with information on the increase in sag which may occur.

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