UNITED STATES DEPARTMENT OF AGRICULTURE
Rural Utilities Service

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SUBJECT: <u>The Mechanics of Overhead Distribution Line Conductors</u>

TO: RUS Electric Borrowers and RUS Electric Staff

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AVAILABILITY: This bulletin is available on the Rural Utilities Service website at http://www.usda.gov/rus/electric.

PURPOSE: The purpose of this guide bulletin is to present and explain:

- The equations needed to calculate ruling spans and conductor sags and tensions,
- The guidelines for preparing or selecting sag-tension tables, and,
- The characteristics, behavior, installation and aeolian vibration of distribution line conductors.

July 30, 2003

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ABBREVIATIONS

ACSR   Aluminum conductor, steel reinforced
 ANSI   American National Standards Institute
  CFR   Code of Federal Regulations
NESC   National Electrical Safety Code
  RUS   Rural Utilities Service
    ^{o}F   degrees Fahrenheit
    ^{o}C   degrees Celsius

THE MECHANICS OF OVERHEAD DISTRIBUTION LINE CONDUCTORS

1. INTRODUCTION

1.1 <u>Scope of Bulletin</u>: This bulletin presents the methodology and equations required to calculate distribution line ruling spans and conductor sags and tensions. It explains the guidelines used for preparing or selecting sag-tension tables. The bulletin also explains conductor characteristics, behavior, installation and aeolian vibration.

1.2 <u>National Electrical Safety Code</u>: The bulletin references rules and presents selected data contained in the 2002 Edition of the National Electrical Safety Code (NESC). At the time this bulletin was written, the 2002 Edition was the latest edition of the NESC. All of the references in this bulletin to the NESC are references to the 2002 Edition of the NESC. Periodically the NESC is updated and revised. Users of this bulletin should use the rules and data, as may be revised and renumbered, from the most recent edition of the NESC. Copies of the NESC may be obtained from the Institute of Electrical and Electronic Engineers, Inc., (IEEE) at the following address:

> IEEE Customer Service
> 445 Hoes Lane, P.O. Box 1331
> Piscataway, NJ 08855-1331
> Telephone: 1-800-678-IEEE

2. CONDUCTOR SAG AND TENSION CALCULATIONS

2.1 <u>Mathematics of Conductor Sag</u>: The behavior and movement of a suspended conductor is the most unpredictable variable in distribution line design. Since complex equations are used to calculate the conductor sag curve, some simplifications and approximations are used. The approximations cause small errors. The accuracy of the final calculated results decreases as the curve equation is simplified.

2.2 <u>Catenary and Parabolic Sag Equations</u>: The curved shape of a completely flexible cable suspended between two rigid supports is defined as a catenary. A conductor, although not

2.3 completely flexible, very nearly has this same shape. The equation for the sag of a catenary is expressed in the following hyperbolic equation:

$$D = \left(\frac{T_h}{W}\right) \times \cosh\left(\frac{W \times S}{2 \times T_h} - 1\right)$$

Where:

        D = Vertical conductor sag length at midspan
        T_h = Horizontal component of conductor tension
        S = Horizontal length of the conductor span (between supports)
        W = Unit vertical weight of the conductor (including ice or wind loads)
    cosh = Hyperbolic cosine

2.2.1 The catenary equation can be approximated to the degree of accuracy desired by using MacLaurin's infinite series for hyperbolic functions. In this form, each added term in the series increases the accuracy. The first three terms of the series are:

$$D = \left(\frac{WS^2}{8T_h}\right) + \left(\frac{W}{6T_h}\right)\left(\frac{WS^2}{8T_h}\right)^2 + \left(\frac{4}{10}\right)\left(\frac{W}{6T_h}\right)^2\left(\frac{WS^2}{8T_h}\right)^3$$

2.2.2 Three terms of this equation are usually sufficient for exacting sag calculations. Two terms generally provide the necessary accuracy for long-span transmission lines. A single term satisfies the accuracy requirements for the majority of distribution, subtransmission, and transmission line sag calculations when spans are no more than 1000 feet (300 meters). The first term of the equation is identical to the equation for a parabolic curve. Therefore, for distribution lines and most transmission lines, the midspan span conductor sag is approximated by the first term of the above equation.

2.2.3 The weight of a conductor in a catenary span equation is assumed to be evenly distributed along the conductor sag curve. In a parabolic equation the conductor weight is assumed to be evenly distributed along a straight line between the conductor supports. For relatively short spans with small sags, the difference in weight distribution is generally negligible.

2.2.4 The parabolic equation is used for the great majority of the manual sag and tension calculations for distribution lines. Catenary equations of several terms are used in computer programs where greater accuracy is desired. A distribution design engineer might use the two-term catenary equation to check the sag error of a parabolic calculation for a long crossing span. The catenary equation has larger sag values than the parabolic equation. Only parabolic equations are used hereafter.

2.3 Dead-End Span Sag and Tension Equations: Most conductor sag and tension calculations are theoretically based on a simple dead-end span of conductor supported at equal elevations. The supports are assumed to be rigid. It is also assumed the conductor length does not change with changes in temperature or stress. These assumptions allow calculations to be made with simple equations of the parabolic curve. See Figure 2-1 which illustrates the parabolic conductor sag curve and some of the principal variables.

The following symbols define and are used to represent some of the conductor tension variables of the simple parabolic span:

 T = Total conductor tension at any specified point in the span

 T_h= Horizontal or longitudinal component of tension at any point in the span, assumed to be constant throughout a parabolic span. At the low point of sag, the vertical component of tension is zero, therefore, the horizontal tension is the total tension at that point

 T_v= Vertical component of tension at designated point in the span; unless otherwise indicated, assumed to be the vertical component of tension at the support

 T_r= Resultant conductor tension; unless otherwise indicated, assumed to be the resultant tension at the supports
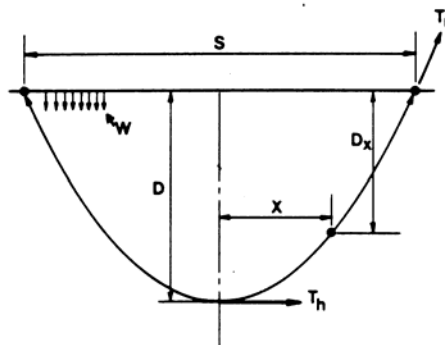
 T_a= Average tension of the conductor span

Figure 2-1: Parabolic Sag Curve

2.3.1 Sag Equations:

The fundamental sag equation for the parabolic sag curve of a conductor span is:

$$D = \frac{W S^2}{8 T_h}$$

Usually W and S are known quantities. A value is assumed or determined for T_h or D and the equation is solved for the unknown variable. If T_h is decreased, D has to increase, and vice versa. If T_h is held constant and the span length is varied, D will increase or decrease as a function of

the square of the span length. This relationship provides the basis for another frequently used sag
equation. In a line section that has a ruling span S_r with the sag D_r, and the same values of W and T_h, the sag D of any given span S can be calculated as follows:

$$D = D_r \left(\frac{S}{S_r} \right)^2$$

Where:

S	=	Span length of span under consideration
S_r	=	Ruling span length
D_r	=	Ruling span sag length

The sag of the conductor at a distance (x) from the midspan or distance (z) from the support can be calculated as follows:

$$D_x = D \left[1 - \left(\frac{2x}{S} \right)^2 \right]$$

$$D_z = D \left[1 - \left(\frac{S - 2z}{S} \right)^2 \right]$$

Where: (See Figure 2.1)

x	=	Distance from midspan
z	=	Distance from support
D_x	=	Sag at point x
D_z	=	Sag at point z

2.3.2 Tension Equations:

The fundamental equations for calculating the various components of conductor tension are:

$$T_h = \frac{WS^2}{8D}$$

$$T_v = \frac{SW}{2}$$

The formula for T_r, based on the Pythagorean theorem, is:

$$T_r = \left(T_h^2 + T_v^2 \right)^{1/2} = T_h \left(1 + \frac{T_v^2}{T_h^2} \right)^{1/2}$$

The following conventional approximation formula may be applied to the above equation for T_r. In the expression $(1+a)^m$, if "a" is much smaller than 1, then $(1+a)^m \cong (1+ma)$. Then, by using this approximation and by substituting the values for T_h and T_v from the formulas above, the following simplified formula for T_r is derived.

$$T_r = T_h + \frac{T_v^2}{2T_h} = T_h + \frac{W^2 S^2}{8T_h} = T_h + WD$$

The average tension of the span is the average of T_h and T_r.

$$T_a = \frac{T_h + T_r}{2}$$

Neither T_h nor T_r is generally known and is calculated. The tensions provided with the sag-tension data for a specific ruling span are usually values of T_a. Since T_a, D, and W are known, T_h can be calculated.

$$T_a = T_h + \frac{WD}{2}$$

$$T_h = T_a - \frac{WD}{2}$$

2.3.3 Conductor Length Equation:

$$L = S\left(1 + \frac{WD}{3T_h}\right) = S\left(1 + \frac{W^2 S^2}{24T_h^2}\right)$$

Where: L = Conductor length along the parabolic sag curve.

2.4 Application of Equations to Actual Design Conditions: The simplified parabolic equations provided in Section 2.3 of this bulletin are sometimes applied to design and actual construction conditions different from the assumed base conditions. The following paragraphs examine the impact of wrongly assumed conditions of most concern.

   a. *The length of installed conductors do not remain constant as assumed.* Conductor materials expand and contract with changes in both temperature and tension. The change of length of the conductor under tension has both elastic and inelastic stretch characteristics. A conductor will never return to exactly the same conditions as when it was installed and sagged. However, by applying equations dealing with the characteristics of conductor behavior, it is possible to predict future conductor sags and tensions for specific temperature and loading conditions.

b. *In actual construction practice, the conductor <u>is not</u> installed and sagged as a single dead-end span between two adjacent, rigid supports as assumed.* The conductor is installed and sagged in one operation in a line section of several unequal spans. The structures between the dead-ends of the stringing section support the conductors with free-wheeling rollers (stringing sheaves or blocks) that permit the conductor to move freely between spans. The behavior of the sag and tension during stringing is a function of the length of conductor between dead-ends rather than a function of the single span where the sagging is done. The behavior of the conductor under these conditions is determined by the "Ruling Span Theory," which is discussed in Section 3.2 of this bulletin.

Once the conductor is sagged and secured to the supporting insulators, the conductor no longer can move freely between spans. The spans, in a sense, become dead-end spans. The supporting structures are not absolutely rigid but will flex when the horizontal tensions between spans are unequal. However, this difference in tension will be minimized if the sagging of the section was done in conformance with the Ruling Span Theory. In practice, this flexure is ignored, and the prediction for future behavior of the spans is based on calculation procedures used for dead-end spans.

c. *The elevations of supporting structures in a stringing section <u>will usually not</u> be exactly equal as assumed.* However, for the great majority of spans, the difference in elevation is small compared to the span length. Therefore, these differences are normally ignored for distribution line designs. Occasionally, wrongly assuming equal elevations of the supporting structures will cause measurable differences between predicted and actual sags. In such cases, design and construction changes may be required. The difference between predicted and actual sags can be minimized by judicious choice of dead-ends for stringing sections.

3. RULING SPAN

3.1 <u>Ruling Span</u>: The term "ruling span" is one of the most frequently used yet misunderstood and misused term in the design, staking, and construction of overhead lines. "Ruling span" is loosely used with several different meanings. The term should be preceded by a descriptive adjective to identify its specific meaning.

3.2 <u>The Ruling Span Theory</u>: During stringing and sagging, the conductors are placed on travelers at the supports and are dead-ended at the ends of the stringing section of the line. While the conductor is on travelers and free to move between spans, the conductor tension and length in any span is a function of the combined average tension of all the spans and the total conductor length of the dead-ended stringing section.

3.2.1 When all the spans have equal lengths and the supports are of equal elevation, the behavior of the conductor in each span will be the same and can be determined by the equations for the dead-end span. When the spans are of unequal length and the supports are of varying elevations,

the mathematics become too complicated to be easily calculated. Therefore, it is necessary to simplify the problem.

3.2.2 By making certain reasonable assumptions concerning the behavior of the conductor in a series of spans supported on travelers, the mathematics can be simplified to a manageable equation. The assumptions for the "Ruling Span Theory" are:

- *The supports are at equal elevations* since the span lengths are large compared to the difference in elevation of supports. (Resultant errors will be negligible.)
- *The horizontal tension is constant throughout the stringing section* since variations in span lengths will not be great enough to cause a measurable difference in the horizontal tension between any two adjacent spans.
- *The uneven spans are replaced by a series of equal spans* such that the total length of the conductor and the horizontal tension of the section is unchanged. Thus the sag and tension characteristics of a single dead-end span can could be used to predict the sag behavior in any of the spans in the section.

3.3 <u>Theoretical Ruling Span</u>: By using the conductor length equation (see Section 2.3 of this bulletin) and by making certain assumptions, approximations, and formula substitutions, the following theoretical ruling span equation can be derived:

$$S_r = \sqrt{\frac{\sum S^3}{\sum S}} = \sqrt{\frac{S^3_1 + S^3_2 + S^3_3 + ... S^3_n}{S_1 + S_2 + S_3 + ... S_n}}$$

Where:

S_r = the theoretical ruling span.
$S_1, S_2, S_3, ... S_n$ are equal to the 1st, 2nd, 3rd ...nth span lengths.

3.3.1 The theoretical ruling span equation is not exact because of the assumptions made. Since its accuracy is sufficient for most line designs, it is the equation used most often to calculate the ruling span for new overhead distribution lines.

3.3.2 Since the horizontal tension and the unit conductor weight are assumed constant throughout the stringing section, the sag of any span in the section can be calculated by the parabolic sag equations given earlier in Section 2.3 of this bulletin.

3.3.3 The above ruling span formula is the ruling span in its true sense. It has been called ruling span, theoretical ruling span, actual ruling span, true ruling span, and equivalent span. It is an equivalent span length based on the total length and average tension of the conductor in a series of spans that is being pulled up and sagged in one operation. It is, therefore, a function of all the spans included in the stringing section.

3.3.4 After being tied in, each span virtually becomes a dead-end span with approximately the same tension as the theoretical ruling span. When the tied spans in the section are of different lengths, changes in temperature, loading and elongation due to creep will cause differences in tension between the spans. These differences in tension will cause a flexing or bending of poles

and arms.

3.3.5 This ruling span "rules" the behavior of the sagged section of line. The sag characteristics of the ruling span set the sag characteristics of every span in the section. If conductors are installed using a sag-tension table with the wrong ruling span, actual final sags and tensions will not be the same as predicted. The greater the difference, the greater the error!

3.4 Design Ruling Span: One or more assumed ruling spans, based on experience, has to be used for the field design of a new line because the theoretical ruling span of a line section cannot be determined until after the line is staked. If the land is reasonably flat, it is appropriate to use a ruling span that approximates the level ground span. The required ground clearance may be subtracted from the attachment height of the lowest conductor to determine the sag limited by ground clearance. This sag value can then be used to determine a ruling span length whose sag is approximately equal to the sag allowed by the basic structure height. For rugged terrain, a ruling span that is longer than the level ground span is usually more effective.

After staking, the theoretical ruling span should be calculated and compared with the design ruling span. Using a design ruling span appreciably different from the theoretical ruling span of the section will produce unpredictable sags and tensions. Slack sags may cause clearance problems while tightly drawn spans may cause uplift problems. Higher than predicted tensions may exceed the permitted load on support assemblies or may cause aeolian vibration problems.

3.5 Estimated Ruling Span: Knowledge gained from a reconnaissance of the proposed line route may make it possible to estimate a ruling span. A traditional "rule of thumb" equation that may be helpful in the estimation of a ruling span is:

S_e = Average Span + 2/3 (Maximum Span – Average Span)

3.5.1 Use this rule for estimating the ruling span with caution! This "rule of thumb," used indiscriminately, has significantly different sags and tensions than the true ruling span equation. Even one span much longer than the average span may cause the estimated ruling span to be much greater than the actual theoretical ruling span. This formula should only be used for estimating the ruling span when the actual spans are not yet known. When the spans are known, the theoretical equation should be used.

3.5.2 The estimated ruling span equation (S_e) is easily solved and convenient for field use. When an engineering calculator is available, use of the following equation provides greater accuracy:

$$S_e = \sqrt{\dfrac{\left[\dfrac{\left(\sum S - S_m\right)^3 + S_m^{\ 3}}{(N-1)^2}\right]}{\sum S}}$$

Where:

    S_e = Estimated ruling span
    $\sum S$ = Estimated total length of all spans in stringing section
    N = Estimated number of spans in stringing section
    S_m = Length of the estimated longest span in stringing section

Another form of the estimated ruling span equation (S_e) is:

$$S_e = \sqrt{\left(N_e S_a^{\ 3} + S_m^{\ 3}\right)\big/\left(N_e S_a + S_m\right)}$$

Where:

    N_e = Estimated number of spans in stringing section, exclusive of the longest span
    S_a = Estimated average span of stringing section, exclusive of the longest span
    S_m = Length of the estimated longest span in stringing section

3.6 **Effects of the Wrong Ruling Span:** The greater the difference between the theoretical ruling span and the design ruling span, the greater the variation will be between the actual and predicted sag and tension values. The magnitude by which actual sags and tensions will differ from the predicted values is a function of conductor temperature and loading.

- If the **design sag is greater than the theoretical sag**, then the actual sag of the installed conductors will be less than the predicted sag. This condition will lead to increased conductor tensions, which may exceed the permitted loads of support structures and guying assemblies.
- If the **design sag is less than the theoretical sag**, then the actual sag of the installed conductors will be greater than the predicted sag. This condition may result in inadequate ground clearances.

4. CONDUCTOR SAG–TENSION TABLES

4.1 Sag–Tension Behavior Under Operating Conditions: The sag and tension equations given in Section 2.3 of this bulletin are valid only when the conductor length does not significantly change. Conductor lengths, and thus their sags, do change while in service. Conductor lengths (and tensions and sags) continuously and simultaneously change due to:

- Temperature fluctuations
- Added ice or wind (weight) loads
- Stretching (creep) because of tension or stress

4.1.1 Since most conductor length changes can be estimated, sag and tension tables can be prepared accordingly. Tables used in line design need to be able to predict the behavior of the conductor sags and tensions under expected future operating conditions. Future conductor sags have to be known to determine compliance with required clearances and separations. Maximum conductor tensions need to be known to determine whether the line will be in compliance with NESC strength requirements for supporting structures and assemblies.

4.1.2 Future conductor sags and tensions are dependent on the tensions placed on the conductors when installed. The sag and tension behavior for a dead-ended span can be predicted for changing conductor loading, temperature, tension, and creep if its temperature and sag or tension are known when the conductor is installed. Consequently, controlling the initial sagging tension will control the long-term behavior of the conductor.

4.2 Preparation of Sag-Tension Tables: The calculations required to predict the sag and tension behavior of a conductor are complicated and are usually performed with sophisticated computer programs. The calculations involve the simultaneous application of equations for sag-tension relationships, conductor stress–strain characteristics, and change in conductor length as a function of conductor temperature. The following data needs to be inputted to the computer program:

- The (theoretical) ruling span,
- The span length,
- Conditions of conductor temperatures and loading (e.g., NESC Loading District),
- Conductor limiting tension condition(s), and
- The specific sag-tension characteristics of the conductor.

4.2.1 The program determines:

- Which limiting conductor tension will control the design;
- Whether final sags will be controlled by the maximum tension or by conductor creep; and
- The initial and final sags and tensions for all specified conditions.

4.2.2 The results of the conductor design data calculated by the computer are usually arranged to form a sag–tension (and stringing) table. Alternative conductor designs can be obtained by changing one or more of the input variables. Alternative conductor designs can be used to determine the most practical design for a particular distribution line. The prepared or selected sag-tension table is then used for detailed staking and conductor installation.

5. CONDUCTOR DESIGN TENSIONS AND TENSION LIMITS

5.1 Design Tension Limits: A conductor's calculated sag and tension is based on a given design ruling span, the conductor's size and type, loading conditions, and a previously established or specified tension limit. Only one tension limit will control the design. If the temperature and loading conditions are held constant, the design may possibly shift to another tension limit for different ruling spans. Tension limits may be specified or required for any of the reasons discussed in Sections 5.2 through 5.4 of this bulletin.

5.2 NESC Conductor Tension Limits: Rule 261H1b of the NESC sets maximum conductor tension limits at 15° C (60° F), without external loads, at:

- Initial unloaded tension: 35 % of rated conductor breaking strength
- Final unloaded tension: 25 % of rated conductor breaking strength

5.3 Other Conductor Tension Limits: The NESC tension limits for standard ACSR and some self-damping conductors can generally be used for typical rural distribution lines. The NESC conductor tension limits need to be reduced by 5 percent for all-aluminum conductors. Moreover, conductor tensions may need to be further reduced in areas prone to aeolian vibration. Conductor manufacturers' recommended tension limits should never be exceeded.

Usually conductor tension limits are expressed in percent of the conductor's breaking or ultimate strength. Listings of the most common distribution conductors, their ultimate strengths, and wind and ice loading by NESC loading district are published as Exhibit A in RUS Bulletin 1724E-153, "Electric Distribution Line Guys and Anchors." The calculation of tension limits, as a percentage of the conductor's breaking strength, is left to the reader.

5.4 Tension Limits Based on Construction Assemblies:. Conductor tensions need to be designed such that they will always be less than the permitted load on supporting structures, pole-top, guy, and anchor assemblies. The NESC requires that all conductor tensions, wind, and ice loads, exerted on poles and assemblies be multiplied by the appropriate overload factors in Table 253-1 of the NESC to obtain permitted tensions and loading. Simultaneously, the NESC requires that all load handling capabilities of poles and assemblies have to be multiplied by the appropriate strength factors of Table 261-1A of the NESC which, in turn, yields "permitted" loads or loading. (The NESC requires that adverse weather conditions, land use and traffic expectations near power lines be considered in the design and upgrading of overhead distribution lines with regards to loading and clearances above ground and between conductors.)

5.4.1 Rule 277 of the 2002 NESC sets the maximum loads (tension) that can be applied to insulators as follows:

- Cantilever *(transverse)* loads: 40 % of rated ultimate strength of insulator
- Tension loads: 50 % of rated ultimate strength of insulator

The ultimate strength ratings of the various sizes and types of standard insulators are published in the various ANSI C-29 standards for insulators.

5.4.2 Generally, the permitted loads for all of the pole-top, guy and anchor assemblies are shown on the design parameters on the assembly drawings or tables in the RUS specifications and drawings for overhead distribution line construction. These permitted loads were calculated by multiplying the assembly's ultimate or designated load (strength) by the appropriate NESC strength factors. Permitted insulator loads are factored into the design parameters on RUS drawings.

6. CONTROLLING AEOLIAN VIBRATION

6.1 <u>Conductor Vibration:</u> Overhead distribution line designs need to be analyzed to assure that wind-produced conductor vibration will not cause failures or damage. Almost every rural distribution line will experience some aeolian vibration. Some locations and prevalent weather conditions may affect certain line designs and produce amplitude and vibration frequencies which will cause fatigue failure of the conductor or structure components.

6.1.1 Because so many factors are involved, it is extremely difficult to establish one set of guidelines applicable to all conductor designs. The purpose here is to provide general and useful information in evaluating potential aeolian vibration problems with a particular line design.

6.1.2 Much has been published concerning the theory of aeolian vibration. This literature provides only general information because each line has unique parameters that might cause line vibrations. More specific design information can be obtained from computer simulations that use large databases for modeling a particular line design. When vibration damage conditions are expected, obtain assistance from a conductor vendor or from consultants.

6.2 <u>Aeolian Vibration Theory:</u> When a steady wind blows across a conductor under tension, wind vortices are detached at regular intervals on the lee side, alternately from the top and bottom, of the conductor. As each of these vortices of wind detach, they impress a minute vertical force on the conductor. The conductor is thus repeatedly subjected to forces alternately impressed from above and below. The frequency of force application to the conductor increases with increasing wind velocity and with decreasing conductor diameter.

6.2.1 If the frequency of the applied forces is approximately the same as the resonant frequency of vibration of the span, the conductor will tend to vibrate in many loops in a vertical plane. The forces impressed by the wind on the conductor produce traveling waves that move away from the points of application of the forces toward the ends of the span. At the span ends the traveling waves are reflected and are superimposed on the inwardly traveling waves, thereby producing standing waves which have frequencies that are multiples of the fundamental frequency of the entire span. Each wave stores part of the energy it receives from the wind during the course of its travel in the form of increased amplitude. The crests becomes higher and the troughs deeper. The balance of energy received from the wind is dissipated as friction between the conductor strands as they are flexed and rubbed together because of the wave.

6.2.2 When a wave reaches the end of an undamped span and is reflected, neither its amplitude nor its stored energy is significantly reduced by the reflection. During its subsequent travel, the wave acquires more energy and greater amplitude from the wind-induced vortices. Ultimately, an equilibrium amplitude is reached in which the input energy equals the dissipated energy. The wave amplitude reached at equilibrium may be large enough to damage the conductor or its supporting assemblies.

6.3 **Factors Affecting Vibration:** A conductor's size, tension, and span length, together, primarily affect a line's susceptibility to aeolian vibration. The amount of energy imparted to a conductor varies directly with the span length. The longer the span, the more wind-induced energy is absorbed. Conductors tend to vibrate more readily at higher tensions because their self-damping ability (the frictional interaction between strands) is reduced.

6.3.1 In rough terrain the winds are more turbulent and the conductors are less apt to vibrate. If the line runs through a wooded area, or runs parallel to the prevailing winds, vibration will generally not be a problem. In most places, winds in excess of about 15 miles per hour (24 kilometers per hour) will be so turbulent they will not produce vibration. However, winds up to 35 miles per hour (56 kilometers per hour) have produced vibrations in conductors crossing level terrain and wide rivers.

6.3.2 The damping properties of the materials in the conductor's supporting structures and assemblies' material may have a minor effect on conductor vibration. Higher poles with greater conductor ground clearance have a greater exposure to vibration-producing winds. Turbulence lessens with height above ground. Rural distribution lines have minimal damaging aeolian vibration because their conductors are relatively close to the ground.

6.3.3 None of the available conductor ties or clamps are manufactured specifically to minimize vibration. Armor rods reinforce the conductor and do a small amount of damping. None of these devices alone provide adequate protection against aeolian vibration for most rural distribution lines.

6.4 **System Experience with Aeolian Vibration:** One of the best guides to use in determining vulnerability to aeolian vibration is historic experience with existing designs used on the system and neighboring systems. Utility personnel are generally aware of the locations, conditions, and

severity of past problems. This knowledge can be very useful in selecting designs and criteria for new lines and modified lines. Design changes in ruling spans, conductor tension, or pole height may either increase or decrease the probability of vibration fatigue damage. Past experience has shown that if lines of a given design have not had aeolian vibration problems, new lines with the same conductor, ruling span, pole height, and wind exposure will probably not have problems. However, some new lines may unexpectedly require additional aeolian vibration protection.

6.5 Aeolian Vibration Mitigation Measures: The following design and installation changes should help to minimize the probability of aeolian vibration of a new distribution line.

Each of the following measures assumes that all other variables remain constant:

- Decrease the span length – longer spans are more susceptible to aeolian vibration;
- For a given sagging temperature, decrease the sagging tension;
- Increasing the size of a particular conductor type without changing the tension will generally decrease the probability of vibration damage;
- Properly sizing and installing Stockbridge-type dampers will generally provide adequate vibration protection for large ACSR distribution conductors. Spiral-type and other less costly impact dampers may provide adequate protection for small ACSR and all-aluminum conductors; and
- Use ACSR conductors with higher percentages of steel because they have better self-damping characteristics than ACSR conductors with smaller percentages of steel. ACSR conductors have better self-damping characteristics than all-aluminum conductors. (There may be need for reducing the design sagging tension when making such substitutions.)

6.6 Other Design Guides: Generally, for distribution lines with average span lengths, aeolian vibration damage will be eliminated if the design initial tensions at 60°F (15°C) are at or below 12 percent of the ultimate strength of the conductor. In some cases, the sags produced by these low stringing tensions may not be feasible or economically sound. In some designs, such as with extra large conductors, lower tensions may already be required such that the permitted loads on assemblies are not exceeded. If each span in the line has adequate ground clearance, a design with a small increase in sag and decrease in tension may be an economical way to lessen the probability of aeolian vibration.

In summary, where conditions warrant concern, conductor spans should be as short as possible and the tensions as low as possible to lessen the probability of aeolian vibration.

7. COORDINATION OF CONDUCTOR SAGS

7.1 Basic Coordination Concepts: When selecting a conductor sag–tension design, the relative sags of all the conductors located on the same supporting structure need to be considered. It is often necessary to use different stringing sags for unlike conductors. It may be necessary to select the sag of one conductor as the base for the sag–tension design of another conductor. Generally, sag coordination is more of a problem for long span construction than for

short span construction. The most common sag coordination problems occur between the center or lower phase conductor and the (often reduced size) neutral.

7.1.1 Other than NESC separation requirements, there are no hard and fast rules for conductor sag coordination. There are four optimum coordination goals. Usually only one or two of these goals can be achieved because the goals tend to conflict with one another. Consequently, compromises need to be made. The four coordination goals are:

- Provide simplified sagging where the phase and neutral conductor initial sags will be the same;
- Provide the best appearance such that the phase and neutral conductor final sags will be the same at normal operating temperatures;
- Provide maximum level ground span where the neutral sag is based on the maximum allowable tension; and
- Eliminate span limitations. (The phase and neutral conductor sag coordination is not a span limiting condition for the great majority of spans.)

7.1.2 It is convenient for the sagging crew to sag the phase and neutral conductors at the same value. However, the sags of unlike conductors will differ in the future because of different conductor material and loading conditions. Sag–tension data for both conductors need to be examined for all limiting conditions.

7.1.3 Section 23 and Appendix A of the NESC sets forth the rules and distances for the various clearances of overhead supply conductors. NESC Rule 232 and Table 232-1 (and its footnotes) specify conductor vertical clearances above ground and other surfaces. This rule and table specify supply conductor separation and clearances in each direction from: each other, other conductors, supports, equipment, etc. NESC Rule 235C specifies conditions under which designers have to determine the required vertical clearances between line conductors (see NESC Table 235-5).

7.1.4 Compliance with the NESC clearance and separation rules may require one or more of the following design changes that might further compromise the coordination goals stated earlier in this section of this bulletin:

- Increase the separation at the supports or use offset neutral brackets;
- Increase the neutral conductor sag *(Check ground clearance and separation to underbuilt cables.)*; and
- Decrease the phase conductor sag as required by increasing its tension or using shorter spans.

7.1.5 Some corrective methods may produce tensions above the permitted design limits, inadequate ground or conductor clearances or may require more or taller poles. The most economical corrective measure(s), required to comply with the NESC and the design criteria, should be chosen.

7.2 Sag Matching Procedures: Specifying tension limits usually controls sag-tension computations. However, it is possible to design with a desired sag condition. This procedure is used to coordinate the sag of one conductor type with another conductor type with known or desired sag.

7.2.1 Most sag–tension computer programs have sag matching capabilities. A sag matching case is generally computed using only one span length. For this computation, all of the tension limits need to be eliminated so that there is only one limiting condition.

7.2.2 If the utilized computer program does not have sag matching capability, the tension can be calculated manually by using the parabolic sag and tension equations provided in Section 2.3 of this bulletin. For the given conductor final loaded condition the sag; first calculate T_h, then T_r, and finally T_a. Use T_a as the only tension limit for the sag–tension computation. Check the results to determine if any required tension limits are exceeded.

7.2.3 To optimize a level ground span design, start the sag coordination procedure with the neutral as the base conductor. Select the design tension that will satisfy all of the requirements and as many of the goals discussed previously. Then select the phase conductor sag–tension design to coordinate with the neutral. If the resulting design exceeds any tension or conductor separation limits, then shift the basis of design to the (usually center or lowest) phase conductor. Reduce the phase conductor tension as needed and coordinate the neutral conductor design to the phase conductor.

7.3 Impact of Conductor Materials: Coordination of the phase and neutral conductors may impact the choice of conductor types and sizes used for the design. The two most important conductor characteristics that should be considered in sag coordination are the rated stress and the temperature coefficient of expansion.

7.3.1 All **conductors of like composition** have essentially the same rated stress. (Rated stress is the rated strength divided by the cross-sectional area.) All ACSR conductors with the same ratio of aluminum to steel stranding have essentially the same stress–strain characteristics and temperature coefficients. Conversely, ACSR conductors with different stranding have different stress-strain and temperature characteristics. Sag coordination is usually the easiest for conductors of like composition. Without ice or wind loads they will creep to nearly the same final sag. When loaded, a small conductor will stretch more than a large conductor because it carries a larger ice load in proportion to its area. Thus, if similar but different sized conductors have the same initial sag, the final sag of the smaller conductor will be greater if the final sag is a function of loading. If the final sag is a function of creep, the final sags will be very nearly the same.

7.3.2 Sag coordination can be a problem if the upper conductor has lower rated stress than the lower conductor. Generally, conductors with lower rated stresses will strain more under tension, will creep more, and will have a greater permanent stretch. Thus, if the conductors have the same initial sag, the one with the lower rated stress will usually have a greater final sag. It is usually desirable for the upper conductor to have sag equal to or less than the lower conductor.

However, heavy ice loads may cause a phase conductor to sag into the neutral conductor. This possibility needs to be examined in the design.

7.3.3 Aluminum has a larger **coefficient of temperature expansion** than steel. (The coefficient of temperature expansion is the unit change in length per unit change in temperature.) Therefore, an all-aluminum conductor will expand more than an ACSR conductor with an increase in temperature. The behavior of ACSR conductors will vary with the ratio of aluminum to steel in the conductor. As the temperature rises, the load carried by the aluminum strands transfers to the steel, which eventually will carry the entire load. Sag is then a function of the coefficient of expansion of steel and the stress applied to the steel strands. The transfer occurs at approximately 100°F (38°C) for (6/1) and (26/7) strand ACSR conductors, and at approximately 167°F (75°C) for (18/1) strand conductors.

7.3.4 At high temperatures the applied stress is small; therefore, sag is more a function of expansion due to temperature than to stress. Thus ACSR conductors with large aluminum-to-steel ratios will sag more at high temperatures than will ACSR conductors with lower ratios. When using all-aluminum and ACSR (18/1) phase conductors at high operating temperatures, phase-to-neutral coordination may be a problem independent of conductor composition.

EXHIBIT A: CONTRIBUTORS

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