13

Transmission Line Parameters

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The power transmission line is one of the major components of an electric power system. Its major function is to transport electric energy, with minimal losses, from the power sources to the load centers, usually separated by long distances. The design of a transmission line depends on four electrical parameters:

1. Series resistance
2. Series inductance
3. Shunt capacitance
4. Shunt conductance

The series resistance relies basically on the physical composition of the conductor at a given temperature. The series inductance and shunt capacitance are produced by the presence of magnetic and electric fields around the conductors, and depend on their geometrical arrangement. The shunt conductance is due to leakage currents flowing across insulators and air. As leakage current is considerably small compared to nominal current, it is usually neglected, and therefore, shunt conductance is normally not considered for the transmission line modeling.

13.1 Equivalent Circuit

Once evaluated, the line parameters are used to model the transmission line and to perform design calculations. The arrangement of the parameters (equivalent circuit model) representing the line depends upon the length of the line.

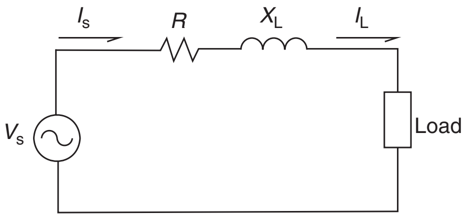

FIGURE 13.1 Equivalent circuit of a short-length transmission line.

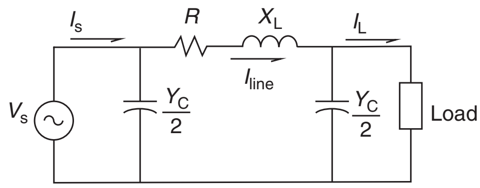

FIGURE 13.2 Equivalent circuit of a medium-length transmission line.

A transmission line is defined as a short-length line if its length is less than 80 km (50 miles). In this case, the shut capacitance effect is negligible and only the resistance and inductive reactance are considered. Assuming balanced conditions, the line can be represented by the equivalent circuit of a single phase with resistance R, and inductive reactance X_L in series (series impedance), as shown in Fig. 13.1. If the transmission line has a length between 80 km (50 miles) and 240 km (150 miles), the line is considered a medium-length line and its single-phase equivalent circuit can be represented in a nominal π circuit configuration [1]. The shunt capacitance of the line is divided into two equal parts, each placed at the sending and receiving ends of the line. Figure 13.2 shows the equivalent circuit for a medium-length line.

Both short- and medium-length transmission lines use approximated lumped-parameter models. However, if the line is larger than 240 km, the model must consider parameters uniformly distributed along the line. The appropriate series impedance and shunt capacitance are found by solving the corresponding differential equations, where voltages and currents are described as a function of distance and time. Figure 13.3 shows the equivalent circuit for a long line.

The calculation of the three basic transmission line parameters is presented in the following sections [1–7].

13.2 Resistance

The AC resistance of a conductor in a transmission line is based on the calculation of its DC resistance. If DC current is flowing along a round cylindrical conductor, the current is uniformly distributed over its cross-section area and its DC resistance is evaluated by

$$R_{DC} = \frac{\rho l}{A} \; (\Omega) \tag{13.1}$$

where ρ = conductor resistivity at a given temperature (Ω-m)
l = conductor length (m)
A = conductor cross-section area (m^2)

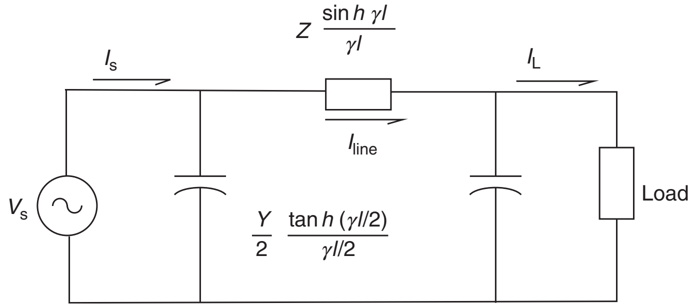

FIGURE 13.3 Equivalent circuit of a long-length transmission line. $Z = zl$ = equivalent total series impedance (Ω), $Y = yl$ = equivalent total shunt admittance (S), z = series impedance per unit length (Ω/m), y = shunt admittance per unit length (S/m), $\gamma = \sqrt{Z\,Y}$ = propagation constant.

If AC current is flowing, rather than DC current, the conductor effective resistance is higher due to frequency or skin effect.

13.2.1 Frequency Effect

The frequency of the AC voltage produces a second effect on the conductor resistance due to the nonuniform distribution of the current. This phenomenon is known as skin effect. As frequency increases, the current tends to go toward the surface of the conductor and the current density decreases at the center. Skin effect reduces the effective cross-section area used by the current, and thus, the effective resistance increases. Also, although in small amount, a further resistance increase occurs when other current-carrying conductors are present in the immediate vicinity. A skin correction factor k, obtained by differential equations and Bessel functions, is considered to reevaluate the AC resistance. For 60 Hz, k is estimated around 1.02

$$R_{AC} = R_{AC}k \tag{13.2}$$

Other variations in resistance are caused by

- Temperature
- Spiraling of stranded conductors
- Bundle conductors arrangement

13.2.2 Temperature Effect

The resistivity of any conductive material varies linearly over an operating temperature, and therefore, the resistance of any conductor suffers the same variations. As temperature rises, the conductor resistance increases linearly, over normal operating temperatures, according to the following equation:

$$R_2 = R_1\left(\frac{T + t_2}{T + t_1}\right) \tag{13.3}$$

where R_2 = resistance at second temperature t_2
R_1 = resistance at initial temperature t_1
T = temperature coefficient for the particular material (°C)

Resistivity (ρ) and temperature coefficient (T) constants depend upon the particular conductor material. Table 13.1 lists resistivity and temperature coefficients of some typical conductor materials [3].

13.2.3 Spiraling and Bundle Conductor Effect

There are two types of transmission line conductors: overhead and underground. Overhead conductors, made of naked metal and suspended on insulators, are preferred over underground conductors because of the lower cost and easy maintenance. Also, overhead transmission lines use aluminum conductors, because of the lower cost and lighter weight compared to copper conductors, although more cross-section area is needed to conduct the same amount of current. There are different types of commercially available aluminum conductors: aluminum-conductor-steel-reinforced (ACSR), aluminum-conductor-alloy-reinforced (ACAR), all-aluminum-conductor (AAC), and all-aluminum-alloy-conductor (AAAC).

TABLE 13.1 Resistivity and Temperature Coefficient of Some Conductors

Material	Resistivity at 20°C (Ω-m)	Temperature Coefficient (°C)
Silver	1.59×10^{-8}	243.0
Annealed copper	1.72×10^{-8}	234.5
Hard-drawn copper	1.77×10^{-8}	241.5
Aluminum	2.83×10^{-8}	228.1

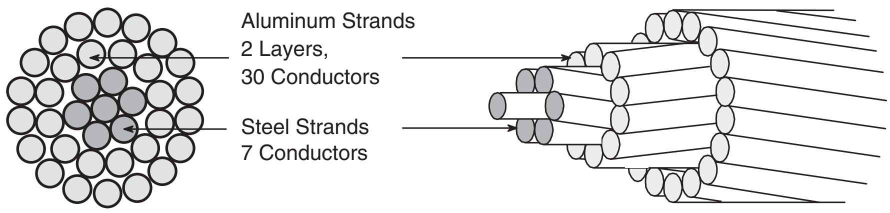

FIGURE 13.4 Stranded aluminum conductor with stranded steel core (ACSR).

ACSR is one of the most used conductors in transmission lines. It consists of alternate layers of stranded conductors, spiraled in opposite directions to hold the strands together, surrounding a core of steel strands. Figure 13.4 shows an example of aluminum and steel strands combination.

The purpose of introducing a steel core inside the stranded aluminum conductors is to obtain a high strength-to-weight ratio. A stranded conductor offers more flexibility and easier to manufacture than a solid large conductor. However, the total resistance is increased because the outside strands are larger than the inside strands on account of the spiraling [8]. The resistance of each wound conductor at any layer, per unit length, is based on its total length as follows:

$$R_{\text{cond}} = \frac{\rho}{A}\sqrt{1 + \left(\pi \frac{1}{p}\right)^2}\ (\Omega/\text{m}) \tag{13.4}$$

where R_{cond} = resistance of wound conductor (Ω)

$\sqrt{1 + \left(\pi \frac{1}{p}\right)^2}$ = length of wound conductor (m)

$p_{\text{cond}} = \frac{l_{\text{turn}}}{2r_{\text{layer}}}$ = relative pitch of wound conductor

l_{turn} = length of one turn of the spiral (m)

$2r_{\text{layer}}$ = diameter of the layer (m)

The parallel combination of n conductors, with same diameter per layer, gives the resistance per layer as follows:

$$R_{\text{layer}} = \frac{1}{\sum_{i=1}^{n} \frac{1}{R_i}}\ (\Omega/\text{m}) \tag{13.5}$$

Similarly, the total resistance of the stranded conductor is evaluated by the parallel combination of resistances per layer.

In high-voltage transmission lines, there may be more than one conductor per phase (bundle configuration) to increase the current capability and to reduce corona effect discharge. Corona effect occurs when the surface potential gradient of a conductor exceeds the dielectric strength of the surrounding air (30 kV/cm during fair weather), producing ionization in the area close to the conductor, with consequent corona losses, audible noise, and radio interference. As corona effect is a function of conductor diameter, line configuration, and conductor surface condition, then meteorological conditions play a key role in its evaluation. Corona losses under rain or snow, for instance, are much higher than in dry weather.

Corona, however, can be reduced by increasing the total conductor surface. Although corona losses rely on meteorological conditions, their evaluation takes into account the conductance between conductors and between conductors and ground. By increasing the number of conductors per phase, the total cross-section area increases, the current capacity increases, and the total AC resistance decreases proportionally to the number of conductors per bundle. Conductor bundles may be applied to any

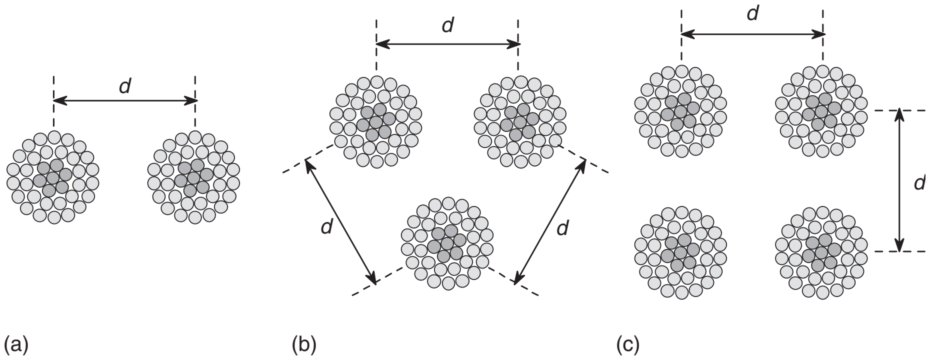

FIGURE 13.5 Stranded conductors arranged in bundles per phase of (a) two, (b) three, and (c) four.

voltage but are always used at 345 kV and above to limit corona. To maintain the distance between bundle conductors along the line, spacers made of steel or aluminum bars are used. Figure 13.5 shows some typical arrangement of stranded bundle configurations.

13.3 Current-Carrying Capacity (Ampacity)

In overhead transmission lines, the current-carrying capacity is determined mostly by the conductor resistance and the heat dissipated from its surface [8]. The heat generated in a conductor (Joule's effect) is dissipated from its surface area by convection and radiation given by

$$I^2R = S(w_c + w_r) \text{ (W)} \tag{13.6}$$

where R = conductor resistance (Ω)
I = conductor current-carrying (A)
S = conductor surface area (sq. in.)
w_c = convection heat loss (W/sq. in.)
w_r = radiation heat loss (W/sq. in.)

Heat dissipation by convection is defined as

$$w_c = \frac{0.0128\sqrt{pv}}{T_{air}^{0.123}\sqrt{d_{cond}}}\,\Delta t \text{ (W)} \tag{13.7}$$

where p = atmospheric pressure (atm)
v = wind velocity (ft/s)
d_{cond} = conductor diameter (in.)
T_{air} = air temperature (kelvin)
Δt = $T_c - T_{air}$ = temperature rise of the conductor (°C)

Heat dissipation by radiation is obtained from Stefan–Boltzmann law and is defined as

$$w_r = 36.8\,E\left[\left(\frac{T_c}{1000}\right)^4 - \left(\frac{T_{air}}{1000}\right)^4\right] \quad \text{(W/sq. in.)} \tag{13.8}$$

where w_r = radiation heat loss (W/sq. in.)
E = emissivity constant (1 for the absolute black body and 0.5 for oxidized copper)
T_c = conductor temperature (°C)
T_{air} = ambient temperature (°C)

Substituting Eqs. (13.7) and (13.8) in Eq. (13.6) we can obtain the conductor ampacity at given temperatures

$$I = \sqrt{\frac{S(w_\mathrm{c} + w_\mathrm{r})}{R}} \quad \text{(A)} \tag{13.9}$$

$$I = \sqrt{\frac{S}{R}\left(\frac{\Delta t\left(0.0128\sqrt{pv}\right)}{T_{\mathrm{air}}^{0.123}\sqrt{d_{\mathrm{cond}}}} + 36.8E\left(\frac{T_\mathrm{c}^4 - T_{\mathrm{air}}^4}{1000^4}\right)\right)} \quad \text{(A)} \tag{13.10}$$

Some approximated current-carrying capacity for overhead ACSR and AACs are presented in the section "Characteristics of Overhead Conductors" [3,9].

13.4 Inductance and Inductive Reactance

A current-carrying conductor produces concentric magnetic flux lines around the conductor. If the current varies with the time, the magnetic flux changes and a voltage is induced. Therefore, an inductance is present, defined as the ratio of the magnetic flux linkage and the current. The magnetic flux produced by the current in transmission line conductors produces a total inductance whose magnitude depends on the line configuration. To determine the inductance of the line, it is necessary to calculate, as in any magnetic circuit with permeability μ, the following factors:

1. Magnetic field intensity H
2. Magnetic field density B
3. Flux linkage λ

13.4.1 Inductance of a Solid, Round, Infinitely Long Conductor

Consider an infinitely long, solid cylindrical conductor with radius r, carrying current I as shown in Fig. 13.6. If the conductor is made of a nonmagnetic material, and the current is assumed uniformly distributed (no skin effect), then the generated internal and external magnetic field lines are concentric circles around the conductor with direction defined by the right-hand rule.

13.4.2 Internal Inductance Due to Internal Magnetic Flux

To obtain the internal inductance, a magnetic field with radius x inside the conductor of length l is chosen, as shown in Fig. 13.7.

The fraction of the current I_x enclosed in the area of the circle chosen is determined by

$$I_x = I\frac{\pi x^2}{\pi r^2} \quad \text{(A)} \tag{13.11}$$

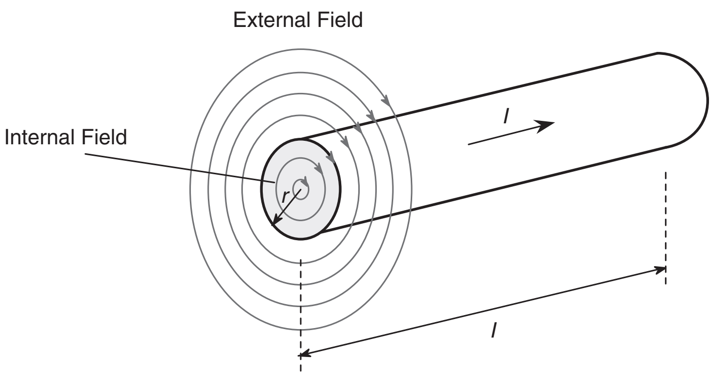

FIGURE 13.6 External and internal concentric magnetic flux lines around the conductor.

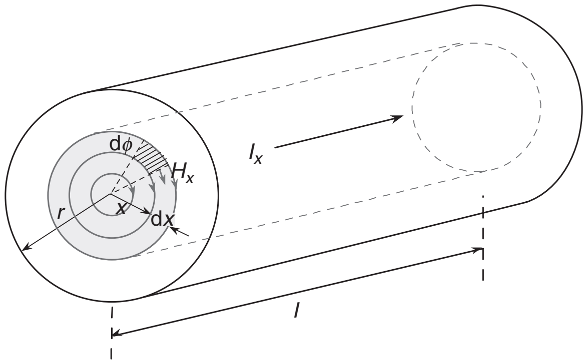

FIGURE 13.7 Internal magnetic flux.

Ampere's law determines the magnetic field intensity H_x, constant at any point along the circle contour as

$$H_x = \frac{I_x}{2\pi x} = \frac{I}{2\pi r^2}\, x \text{ (A/m)} \tag{13.12}$$

The magnetic flux density B_x is obtained by

$$B_x = \mu H_x = \frac{\mu_0}{2\pi}\left(\frac{Ix}{r^2}\right) \text{ (T)} \tag{13.13}$$

where $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m for a nonmagnetic material.

The differential flux $\mathrm{d}\phi$ enclosed in a ring of thickness $\mathrm{d}x$ for a 1-m length of conductor and the differential flux linkage $\mathrm{d}\lambda$ in the respective area are

$$\mathrm{d}\phi = B_x\, \mathrm{d}x = \frac{\mu_0}{2\pi}\left(\frac{Ix}{r^2}\right) \mathrm{d}x \text{ (Wb/m)} \tag{13.14}$$

$$\mathrm{d}\lambda = \frac{\pi x^2}{\pi r^2}\, \mathrm{d}\phi = \frac{\mu_0}{2\pi}\left(\frac{Ix^3}{r^4}\right) \mathrm{d}x \text{ (Wb/m)} \tag{13.15}$$

The internal flux linkage is obtained by integrating the differential flux linkage from $x = 0$ to $x = r$

$$\lambda_{\text{int}} = \int_0^r \mathrm{d}\lambda = \frac{\mu_0}{8\pi} I \text{ (Wb/m)} \tag{13.16}$$

Therefore, the conductor inductance due to internal flux linkage, per unit length, becomes

$$L_{\text{int}} = \frac{\lambda_{\text{int}}}{I} = \frac{\mu_0}{8\pi} \text{ (H/m)} \tag{13.17}$$

13.4.3 External Inductance

The external inductance is evaluated assuming that the total current I is concentrated at the conductor surface (maximum skin effect). At any point on an external magnetic field circle of radius y (Fig. 13.8), the magnetic field intensity H_y and the magnetic field density B_y, per unit length, are

$$H_y = \frac{I}{2\pi y} \text{ (A/m)} \tag{13.18}$$

$$B_y = \mu H_y = \frac{\mu_0}{2\pi}\frac{I}{y} \text{ (T)} \tag{13.19}$$

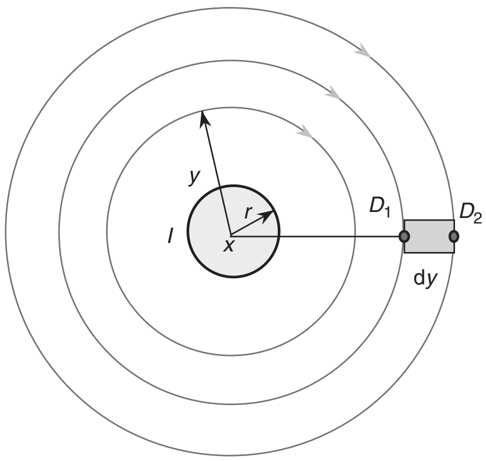

FIGURE 13.8 External magnetic field.

The differential flux $d\phi$ enclosed in a ring of thickness dy, from point D_1 to point D_2, for a 1-m length of conductor is

$$d\phi = B_y \, dy = \frac{\mu_0}{2\pi} \frac{I}{y} \, dy \text{ (Wb/m)} \tag{13.20}$$

As the total current I flows in the surface conductor, then the differential flux linkage $d\lambda$ has the same magnitude as the differential flux $d\phi$.

$$d\lambda = d\phi = \frac{\mu_0}{2\pi} \frac{I}{y} \, dy \text{ (Wb/m)} \tag{13.21}$$

The total external flux linkage enclosed by the ring is obtained by integrating from D_1 to D_2

$$\lambda_{1-2} = \int_{D_1}^{D_2} d\lambda = \frac{\mu_0}{2\pi} I \int_{D_1}^{D_2} \frac{dy}{y} = \frac{\mu_0}{2\pi} I \ln\left(\frac{D_1}{D_2}\right) \text{ (Wb/m)} \tag{13.22}$$

In general, the total external flux linkage from the surface of the conductor to any point D, per unit length, is

$$\lambda_{\text{ext}} = \int_r^D d\lambda = \frac{\mu_0}{2\pi} I \ln\left(\frac{D}{r}\right) \text{ (Wb/m)} \tag{13.23}$$

The summation of the internal and external flux linkage at any point D permits evaluation of the total inductance of the conductor L_{tot}, per unit length, as follows:

$$\lambda_{\text{intl}} + \lambda_{\text{ext}} = \frac{\mu_0}{2\pi} I \left[\frac{1}{4} + \ln\left(\frac{D}{r}\right)\right] = \frac{\mu_0}{2\pi} I \ln\left(\frac{D}{e^{-1/4} r}\right) \text{ (Wb/m)} \tag{13.24}$$

$$L_{\text{tot}} = \frac{\lambda_{\text{int}} + \lambda_{\text{ext}}}{I} = \frac{\mu_0}{2\pi} \ln\left(\frac{D}{\text{GMR}}\right) \text{ (H/m)} \tag{13.25}$$

where GMR (geometric mean radius) $= e^{-1/4} r = 0.7788r$

GMR can be considered as the radius of a fictitious conductor assumed to have no internal flux but with the same inductance as the actual conductor with radius r.

13.4.4 Inductance of a Two-Wire Single-Phase Line

Now, consider a two-wire single-phase line with solid cylindrical conductors A and B with the same radius r, same length l, and separated by a distance D, where $D > r$, and conducting the same current I, as shown in Fig. 13.9. The current flows from the source to the load in conductor A and returns in conductor B ($I_A = -I_B$).

The magnetic flux generated by one conductor links the other conductor. The total flux linking conductor A, for instance, has two components: (a) the flux generated by conductor A and (b) the flux generated by conductor B which links conductor A.

As shown in Fig. 13.10, the total flux linkage from conductors A and B at point P is

$$\lambda_{AP} = \lambda_{AAP} + \lambda_{ABP} \tag{13.26}$$

$$\lambda_{BP} = \lambda_{BBP} + \lambda_{BAP} \tag{13.27}$$

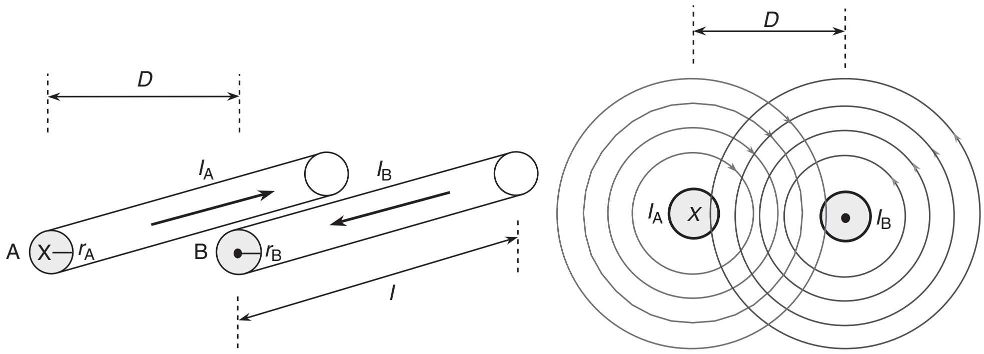

FIGURE 13.9 External magnetic flux around conductors in a two-wire single-phase line.

where λ_{AAP} = flux linkage from magnetic field of conductor A on conductor A at point P
λ_{ABP} = flux linkage from magnetic field of conductor B on conductor A at point P
λ_{BBP} = flux linkage from magnetic field of conductor B on conductor B at point P
λ_{BAP} = flux linkage from magnetic field of conductor A on conductor B at point P

The expressions of the flux linkages above, per unit length, are

$$\lambda_{AAP} = \frac{\mu_0}{2\pi} I \ln\left(\frac{D_{AP}}{\mathrm{GMR_A}}\right) \text{ (Wb/m)} \tag{13.28}$$

$$\lambda_{ABP} = \int_D^{D_{BP}} B_{BP}\,\mathrm{d}P = -\frac{\mu_0}{2\pi} I \ln\left(\frac{D_{BP}}{D}\right) \text{ (Wb/m)} \tag{13.29}$$

$$\lambda_{BAP} = \int_D^{D_{AP}} B_{AP}\,\mathrm{d}P = -\frac{\mu_0}{2\pi} I \ln\left(\frac{D_{AP}}{D}\right) \text{ (Wb/m)} \tag{13.30}$$

$$\lambda_{BBP} = \frac{\mu_0}{2\pi} I \ln\left(\frac{D_{BP}}{\mathrm{GMR_B}}\right) \text{ (Wb/m)} \tag{13.31}$$

The total flux linkage of the system at point P is the algebraic summation of λ_{AP} and λ_{BP}

$$\lambda_P = \lambda_{AP} + \lambda_{BP} = (\lambda_{AAP} + \lambda_{ABP}) + (\lambda_{BAP} + \lambda_{BBP}) \tag{13.32}$$

$$\lambda_P = \frac{\mu_0}{2\pi} I \ln\left[\left(\frac{D_{AP}}{\mathrm{GMR_A}}\right)\left(\frac{D}{D_{AP}}\right)\left(\frac{D_{BP}}{\mathrm{GMR_B}}\right)\left(\frac{D}{D_{BP}}\right)\right] = \frac{\mu_0}{2\pi} I \ln\left(\frac{D^2}{\mathrm{GMR_A GMR_B}}\right) \text{ (Wb/m)} \tag{13.33}$$

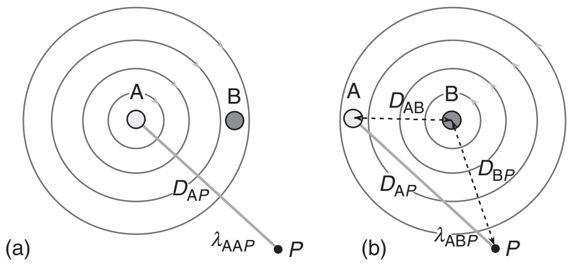

FIGURE 13.10 Flux linkage of (a) conductor A at point P and (b) conductor B on conductor A at point P. Single-phase system.

If the conductors have the same radius, $r_A = r_B = r$, and the point P is shifted to infinity, then the total flux linkage of the system becomes

$$\lambda = \frac{\mu_0}{\pi} I \ln\left(\frac{D}{\mathrm{GMR}}\right) \text{ (Wb/m)} \tag{13.34}$$

and the total inductance per unit length becomes

$$L_{1\text{-phase system}} = \frac{\lambda}{I} = \frac{\mu_0}{\pi} \ln\left(\frac{D}{\text{GMR}}\right) \text{ (H/m)} \tag{13.35}$$

Comparing Eqs. (13.25) and (13.35), it can be seen that the inductance of the single-phase system is twice the inductance of a single conductor.

For a line with stranded conductors, the inductance is determined using a new GMR value named $\text{GMR}_{\text{stranded}}$, evaluated according to the number of conductors. If conductors A and B in the single-phase system, are formed by n and m solid cylindrical identical subconductors in parallel, respectively, then

$$\text{GMR}_{\text{A\_stranded}} = \sqrt[n^2]{\prod_{i=1}^{n}\prod_{j=1}^{n} D_{ij}} \tag{13.36}$$

$$\text{GMR}_{\text{B\_stranded}} = \sqrt[m^2]{\prod_{i=1}^{m}\prod_{j=1}^{m} D_{ij}} \tag{13.37}$$

Generally, the $\text{GMR}_{\text{stranded}}$ for a particular cable can be found in conductor tables given by the manufacturer.

If the line conductor is composed of bundle conductors, the inductance is reevaluated taking into account the number of bundle conductors and the separation among them. The $\text{GMR}_{\text{bundle}}$ is introduced to determine the final inductance value. Assuming the same separation among bundle conductors, the equation for $\text{GMR}_{\text{bundle}}$, up to three conductors per bundle, is defined as

$$\text{GMR}_{n \text{ bundle conductors}} = \sqrt[n]{d^{n-1}\text{GMR}_{\text{stranded}}} \tag{13.38}$$

where n = number of conductors per bundle

$\text{GMR}_{\text{stranded}}$ = GMR of the stranded conductor

d = distance between bundle conductors

For four conductors per bundle with the same separation between consecutive conductors, the $\text{GMR}_{\text{bundle}}$ is evaluated as

$$\text{GMR}_{4 \text{ bundle conductors}} = 1.09\sqrt[4]{d^3\text{GMR}_{\text{stranded}}} \tag{13.39}$$

13.4.5 Inductance of a Three-Phase Line

The derivations for the inductance in a single-phase system can be extended to obtain the inductance per phase in a three-phase system. Consider a three-phase, three-conductor system with solid cylindrical conductors with identical radius r_A, r_B, and r_C, placed horizontally with separation D_{AB}, D_{BC}, and D_{CA} (where $D > r$) among them. Corresponding currents I_A, I_B, and I_C flow along each conductor as shown in Fig. 13.11.

The total magnetic flux enclosing conductor A at a point P away from the conductors is the sum of the flux produced by conductors A, B, and C as follows:

$$\phi_{AP} = \phi_{AAP} + \phi_{ABP} + \phi_{ACP} \tag{13.40}$$

where ϕ_{AAP} = flux produced by current I_A on conductor A at point P

ϕ_{ABP} = flux produced by current I_B on conductor A at point P

ϕ_{ACP} = flux produced by current I_C on conductor A at point P

Considering 1-m length for each conductor, the expressions for the fluxes above are

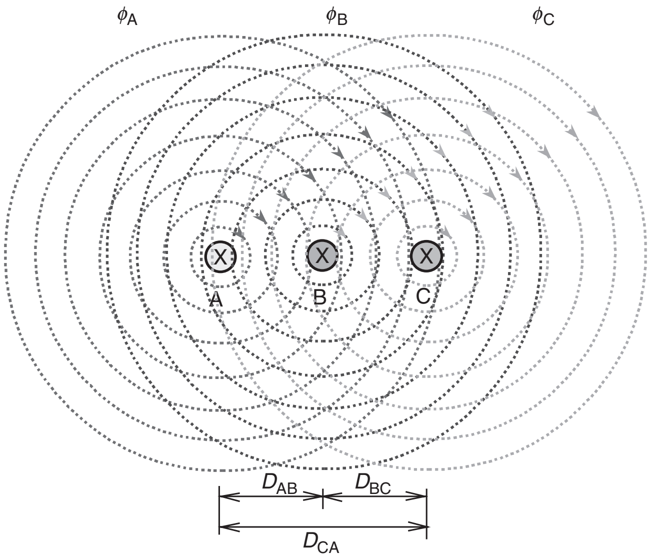

FIGURE 13.11 Magnetic flux produced by each conductor in a three-phase system.

$$\phi_{AAP} = \frac{\mu_0}{2\pi} I_A \ln\left(\frac{D_{AP}}{GMR_A}\right) \text{ (Wb/m)} \tag{13.41}$$

$$\phi_{ABP} = \frac{\mu_0}{2\pi} I_B \ln\left(\frac{D_{BP}}{D_{AB}}\right) \text{ (Wb/m)} \tag{13.42}$$

$$\phi_{ACP} = \frac{\mu_0}{2\pi} I_C \ln\left(\frac{D_{CP}}{D_{AC}}\right) \text{ (Wb/m)} \tag{13.43}$$

The corresponding flux linkage of conductor A at point P (Fig. 13.12) is evaluated as

$$\lambda_{AP} = \lambda_{AAP} + \lambda_{ABP} + \lambda_{ACP} \tag{13.44}$$

having

$$\lambda_{AAP} = \frac{\mu_0}{2\pi} I_A \ln\left(\frac{D_{AP}}{GMR_A}\right) \text{ (Wb/m)} \tag{13.45}$$

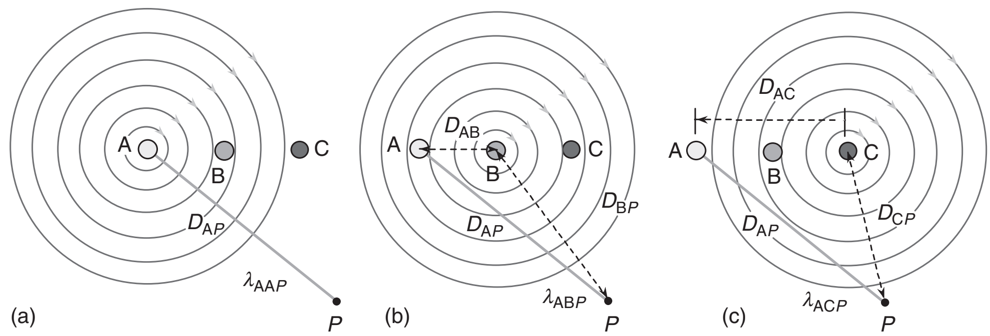

FIGURE 13.12 Flux linkage of (a) conductor A at point P, (b) conductor B on conductor A at point P, and (c) conductor C on conductor A at point P. Three-phase system.

$$\lambda_{ABP} = \int_{D_{AB}}^{D_{BP}} B_{BP}\, dP = \frac{\mu_0}{2\pi} I_B \ln\left(\frac{D_{BP}}{D_{AB}}\right) \text{ (Wb/m)} \tag{13.46}$$

$$\lambda_{ACP} = \int_{D_{AC}}^{D_{CP}} B_{CP}\, dP = \frac{\mu_0}{2\pi} I_C \ln\left(\frac{D_{CP}}{D_{AC}}\right) \text{ (Wb/m)} \tag{13.47}$$

where λ_{AP} = total flux linkage of conductor A at point P

λ_{AAP} = flux linkage from magnetic field of conductor A on conductor A at point P

λ_{ABP} = flux linkage from magnetic field of conductor B on conductor A at point P

λ_{ACP} = flux linkage from magnetic field of conductor C on conductor A at point P

Substituting Eqs. (13.45) through (13.47) in Eq. (13.44) and rearranging, according to natural logarithms law, we have

$$\lambda_{AP} = \frac{\mu_0}{2\pi}\left[I_A \ln\left(\frac{D_{AP}}{\text{GMR}_A}\right) + I_B \ln\left(\frac{D_{BP}}{D_{AB}}\right) + I_C \ln\left(\frac{D_{CP}}{D_{AC}}\right)\right] \text{ (Wb/m)} \tag{13.48}$$

$$\lambda_{AP} = \frac{\mu_0}{2\pi}\left[I_A \ln\left(\frac{1}{\text{GMR}_A}\right) + I_B \ln\left(\frac{1}{D_{AB}}\right) + I_C \ln\left(\frac{1}{D_{AC}}\right)\right] + \frac{\mu_0}{2\pi}\left[I_A \ln(D_{AP}) + I_B \ln(D_{BP}) + I_C \ln(D_{CP})\right] \text{ (Wb/m)} \tag{13.49}$$

The arrangement of Eq. (13.48) into Eq. (13.49) is algebraically correct according to natural logarithms law. However, as the calculation of any natural logarithm must be dimensionless, the numerator in the expressions $\ln(1/\text{GMR}_A)$, $\ln(1/D_{AB})$, and $\ln(1/D_{AC})$ must have the same dimension as the denominator. The same applies for the denominator in the expressions $\ln(D_{AP})$, $\ln(D_{BP})$, and $\ln(D_{CP})$.

Assuming a balanced three-phase system, where $I_A + I_B + I_C = 0$, and shifting the point P to infinity in such a way that $D_{AP} = D_{BP} = D_{CP}$, then the second part of Eq. (13.49) is zero, and the flux linkage of conductor A becomes

$$\lambda_A = \frac{\mu_0}{2\pi}\left[I_A \ln\left(\frac{1}{\text{GMR}_A}\right) + I_B \ln\left(\frac{1}{D_{AB}}\right) + I_C \ln\left(\frac{1}{D_{AC}}\right)\right] \text{ (Wb/m)} \tag{13.50}$$

Similarly, the flux linkage expressions for conductors B and C are

$$\lambda_B = \frac{\mu_0}{2\pi}\left[I_A \ln\left(\frac{1}{D_{BA}}\right) + I_B \ln\left(\frac{1}{\text{GMR}_B}\right) + I_C \ln\left(\frac{1}{D_{BC}}\right)\right] \text{ (Wb/m)} \tag{13.51}$$

$$\lambda_C = \frac{\mu_0}{2\pi}\left[I_A \ln\left(\frac{1}{D_{CA}}\right) + I_B \ln\left(\frac{1}{D_{CB}}\right) + I_C \ln\left(\frac{1}{\text{GMR}_C}\right)\right] \text{ (Wb/m)} \tag{13.52}$$

The flux linkage of each phase conductor depends on the three currents, and therefore, the inductance per phase is not only one as in the single-phase system. Instead, three different inductances (self and mutual conductor inductances) exist. Calculating the inductance values from the equations above and arranging the equations in a matrix form we can obtain the set of inductances in the system

$$\begin{bmatrix}\lambda_A \\ \lambda_B \\ \lambda_C\end{bmatrix} = \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} \\ L_{BA} & L_{BB} & L_{BC} \\ L_{CA} & L_{CB} & L_{CC}\end{bmatrix}\begin{bmatrix} I_A \\ I_B \\ I_C\end{bmatrix} \tag{13.53}$$

where λ_A, λ_B, λ_C = total flux linkages of conductors A, B, and C

L_{AA}, L_{BB}, L_{CC} = self-inductances of conductors A, B, and C field of conductor A at point P

L_{AB}, L_{BC}, L_{CA}, L_{BA}, L_{CB}, L_{AC} = mutual inductances among conductors

With nine different inductances in a simple three-phase system the analysis could be a little more complicated. However, a single inductance per phase can be obtained if the three conductors are arranged with the same separation among them (symmetrical arrangement), where $D = D_{AB} = D_{BC} = D_{CA}$. For a balanced three-phase system ($I_A + I_B + I_C = 0$, or $I_A = -I_B - I_C$), the flux linkage of each conductor, per unit length, will be the same. From Eq. (13.50) we have

$$\lambda_A = \frac{\mu_0}{2\pi}\left[(-I_B - I_C)\ln\left(\frac{1}{\mathrm{GMR_A}}\right) + I_B \ln\left(\frac{1}{D}\right) + I_C \ln\left(\frac{1}{D}\right)\right]$$

$$\lambda_A = \frac{\mu_0}{2\pi}\left[-I_B \ln\left(\frac{D}{\mathrm{GMR_A}}\right) - I_C \ln\left(\frac{D}{\mathrm{GMR_A}}\right)\right]$$

$$\lambda_A = \frac{\mu_0}{2\pi}\left[I_A \ln\left(\frac{D}{\mathrm{GMR_A}}\right)\right] \ (\mathrm{Wb/m}) \tag{13.54}$$

If GMR value is the same for all conductors (either single or bundle GMR), the total flux linkage expression is the same for all phases. Therefore, the equivalent inductance per phase is

$$L_{\mathrm{phase}} = \frac{\mu_0}{2\pi}\ln\left(\frac{D}{\mathrm{GMR_{phase}}}\right) \ (\mathrm{H/m}) \tag{13.55}$$

13.4.6 Inductance of Transposed Three-Phase Transmission Lines

In actual transmission lines, the phase conductors cannot maintain symmetrical arrangement along the whole length because of construction considerations, even when bundle conductor spacers are used. With asymmetrical spacing, the inductance will be different for each phase, with a corresponding unbalanced voltage drop on each conductor. Therefore, the single-phase equivalent circuit to represent the power system cannot be used.

However, it is possible to assume symmetrical arrangement in the transmission line by transposing the phase conductors. In a transposed system, each phase conductor occupies the location of the other two phases for one-third of the total line length as shown in Fig. 13.13. In this case, the average distance geometrical mean distance (GMD) substitutes distance D, and the calculation of phase inductance derived for symmetrical arrangement is still valid.

The inductance per phase per unit length in a transmission line becomes

$$L_{\mathrm{phase}} = \frac{\mu_0}{2\pi}\ln\left(\frac{\mathrm{GMD}}{\mathrm{GMR_{phase}}}\right) \ (\mathrm{H/m}) \tag{13.56}$$

Once the inductance per phase is obtained, the inductive reactance per unit length is

$$X_{L_{\mathrm{phase}}} = 2\pi f L_{\mathrm{phase}} = \mu_0 f \ln\left(\frac{\mathrm{GMD}}{\mathrm{GMR_{phase}}}\right) \ (\Omega/\mathrm{m}) \tag{13.57}$$

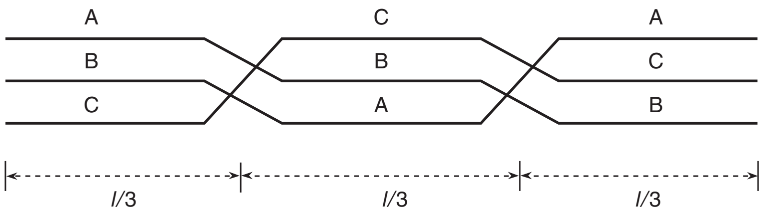

FIGURE 13.13 Arrangement of conductors in a transposed line.

For bundle conductors, the $\text{GMR}_{\text{bundle}}$ value is determined, as in the single-phase transmission line case, by the number of conductors, and by the number of conductors per bundle and the separation among them. The expression for the total inductive reactance per phase yields

$$X_{L_{\text{phase}}} = \mu_0 f \ln\left(\frac{\text{GMD}}{\text{GMR}_{\text{bundle}}}\right) \ (\Omega/\text{m}) \tag{13.58}$$

where $\text{GMR}_{\text{bundle}} = (d^{\,n-1}\ \text{GMR}_{\text{stranded}})^{1/n}$ up to three conductors per bundle (m)
$\text{GMR}_{\text{bundle}} = 1.09(d^4\ \text{GMR}_{\text{stranded}})^{1/4}$ for four conductors per bundle (m)
$\text{GMR}_{\text{phase}}$ = geometric mean radius of phase conductor, either solid or stranded (m)
$\text{GMD} = \sqrt[3]{D_{\text{AB}}D_{\text{BC}}D_{\text{CA}}}$ = geometrical mean distance for a three-phase line (m)
d = distance between bundle conductors (m)
n = number of conductor per bundle
f = frequency (Hz)

13.5 Capacitance and Capacitive Reactance

Capacitance exists among transmission line conductors due to their potential difference. To evaluate the capacitance between conductors in a surrounding medium with permittivity ε, it is necessary to determine the voltage between the conductors, and the electric field strength of the surrounding.

13.5.1 Capacitance of a Single-Solid Conductor

Consider a solid, cylindrical, long conductor with radius r, in a free space with permittivity ε_0, and with a charge of q^+ coulombs per meter, uniformly distributed on the surface. There is a constant electric field strength on the surface of cylinder (Fig. 13.14). The resistivity of the conductor is assumed to be zero (perfect conductor), which results in zero internal electric field due to the charge on the conductor.

The charge q^+ produces an electric field radial to the conductor with equipotential surfaces concentric to the conductor. According to Gauss's law, the total electric flux leaving a closed surface is equal to the total charge inside the volume enclosed by the surface. Therefore, at an outside point P separated x meters from the center of the conductor, the electric field flux density and the electric field intensity are

$$\text{Density}_P = \frac{q}{A} = \frac{q}{2\pi x} \ (\text{C}) \tag{13.59}$$

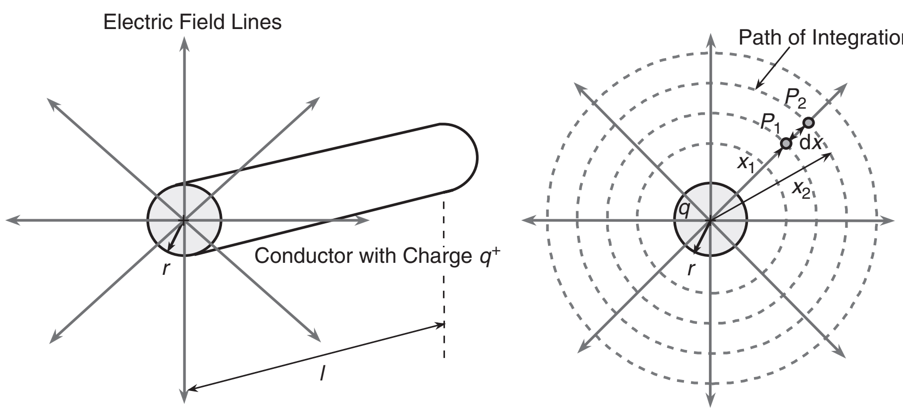

FIGURE 13.14 Electric field produced from a single conductor.

$$E_P = \frac{\text{Density}_P}{\varepsilon} = \frac{q}{2\pi\varepsilon_0 x} \text{ (V/m)} \tag{13.60}$$

where Density_P = electric flux density at point P

E_P = electric field intensity at point P

A = surface of a concentric cylinder with 1-m length and radius x (m^2)

$\varepsilon = \varepsilon_0 = \frac{10^{-9}}{36\pi}$ = permittivity of free space assumed for the conductor (F/m)

The potential difference or voltage difference between two outside points P_1 and P_2 with corresponding distances x_1 and x_2 from the conductor center is defined by integrating the electric field intensity from x_1 to x_2

$$V_{1-2} = \int_{x_1}^{x_2} E_P \frac{\mathrm{d}x}{x} = \int_{x_1}^{x_2} \frac{q}{2\pi\varepsilon_0} \frac{\mathrm{d}x}{x} = \frac{q}{2\pi\varepsilon_0} \ln\left[\frac{x_2}{x_1}\right] \text{ (V)} \tag{13.61}$$

Then, the capacitance between points P_1 and P_2 is evaluated as

$$C_{1-2} = \frac{q}{V_{1-2}} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{x_2}{x_1}\right]} \text{ (F/m)} \tag{13.62}$$

If point P_1 is located at the conductor surface ($x_1 = r$), and point P_2 is located at ground surface below the conductor ($x_2 = h$), then the voltage of the conductor and the capacitance between the conductor and ground are

$$V_{\text{cond}} = \frac{q}{2\pi\varepsilon_0} \ln\left[\frac{h}{r}\right] \text{ (V)} \tag{13.63}$$

$$C_{\text{cond-ground}} = \frac{q}{V_{\text{cond}}} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{h}{r}\right]} \text{ (F/m)} \tag{13.64}$$

13.5.2 Capacitance of a Single-Phase Line with Two Wires

Consider a two-wire single-phase line with conductors A and B with the same radius r, separated by a distance $D > r_A$ and r_B. The conductors are energized by a voltage source such that conductor A has a charge q^+ and conductor B a charge q^- as shown in Fig. 13.15.

The charge on each conductor generates independent electric fields. Charge q^+ on conductor A generates a voltage $V_{\text{AB–A}}$ between both conductors. Similarly, charge q^- on conductor B generates a voltage $V_{\text{AB–B}}$ between conductors.

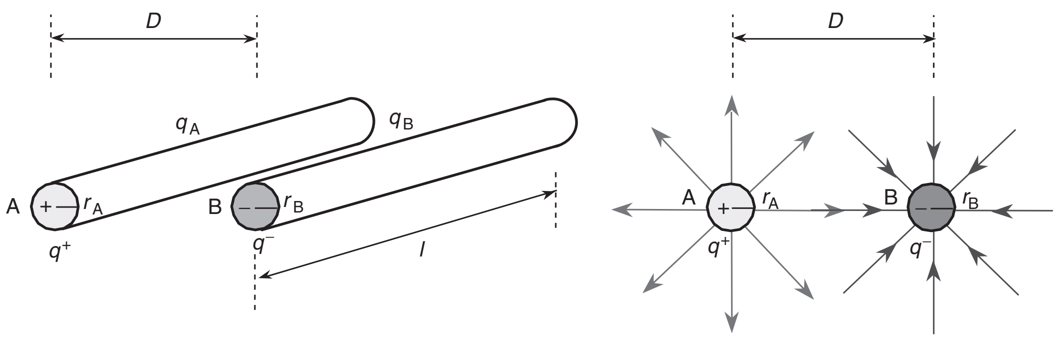

FIGURE 13.15 Electric field produced from a two-wire single-phase system.

V_{AB-A} is calculated by integrating the electric field intensity, due to the charge on conductor A, on conductor B from r_A to D

$$V_{AB-A} = \int_{r_A}^{D} E_A \, dx = \frac{q}{2\pi\varepsilon_0} \ln\left[\frac{D}{r_A}\right] \tag{13.65}$$

V_{AB-B} is calculated by integrating the electric field intensity due to the charge on conductor B from D to r_B

$$V_{AB-B} = \int_{D}^{r_B} E_B \, dx = \frac{-q}{2\pi\varepsilon_0} \ln\left[\frac{r_B}{D}\right] \tag{13.66}$$

The total voltage is the sum of the generated voltages V_{AB-A} and V_{AB-B}

$$V_{AB} = V_{AB-A} + V_{AB-B} = \frac{q}{2\pi\varepsilon_0} \ln\left[\frac{D}{r_A}\right] - \frac{q}{2\pi\varepsilon_0} \ln\left[\frac{r_B}{D}\right] = \frac{q}{2\pi\varepsilon_0} \ln\left[\frac{D^2}{r_A r_B}\right] \tag{13.67}$$

If the conductors have the same radius, $r_A = r_B = r$, then the voltage between conductors V_{AB}, and the capacitance between conductors C_{AB}, for a 1-m line length are

$$V_{AB} = \frac{q}{\pi\varepsilon_0} \ln\left[\frac{D}{r}\right] \text{ (V)} \tag{13.68}$$

$$C_{AB} = \frac{\pi\varepsilon_0}{\ln\left[\frac{D}{r}\right]} \text{ (F/m)} \tag{13.69}$$

The voltage between each conductor and ground (G) (Fig. 13.16) is one-half of the voltage between the two conductors. Therefore, the capacitance from either line to ground is twice the capacitance between lines

$$V_{AG} = V_{BG} = \frac{V_{AB}}{2} \text{ (V)} \tag{13.70}$$

$$C_{AG} = \frac{q}{V_{AG}} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{D}{r}\right]} \text{ (F/m)} \tag{13.71}$$

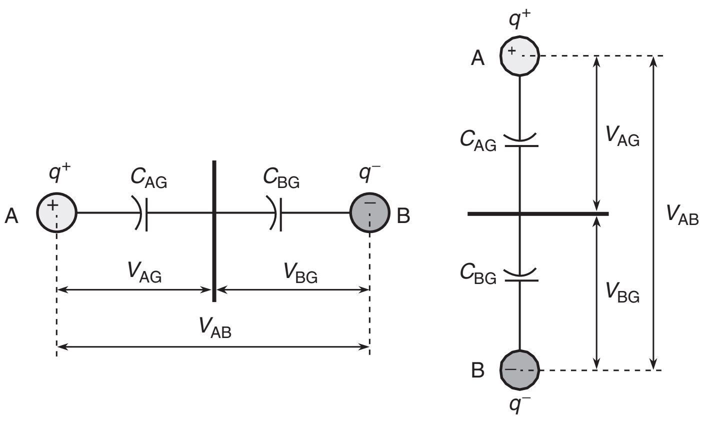

FIGURE 13.16 Capacitance between line to ground in a two-wire single-phase line.

13.5.3 Capacitance of a Three-Phase Line

Consider a three-phase line with the same voltage magnitude between phases, and assuming a balanced system with abc (positive) sequence such that $q_A + q_B + q_C = 0$. The conductors have radii r_A, r_B, and r_C, and the space between conductors are D_{AB}, D_{BC}, and D_{AC} (where D_{AB}, D_{BC}, and $D_{AC} > r_A$, r_B, and r_C). Also, the effect of earth and neutral conductors is neglected.

The expression for voltages between two conductors in a single-phase system can be extended to obtain the voltages between conductors in a three-phase system. The expressions for V_{AB} and V_{AC} are

$$V_{AB} = \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{AB}}{r_A}\right] + q_B \ln\left[\frac{r_B}{D_{AB}}\right] + q_C \ln\left[\frac{D_{BC}}{D_{AC}}\right]\right] \text{ (V)} \tag{13.72}$$

$$V_{AC} = \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{CA}}{r_A}\right] + q_B \ln\left[\frac{D_{BC}}{D_{AB}}\right] + q_C \ln\left[\frac{r_C}{D_{AC}}\right]\right] \text{ (V)} \tag{13.73}$$

If the three-phase system has triangular arrangement with equidistant conductors such that $D_{AB} = D_{BC} = D_{AC} = D$, with the same radii for the conductors such that $r_A = r_B = r_C = r$ (where $D > r$), the expressions for V_{AB} and V_{AC} are

$$\begin{aligned} V_{AB} &= \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D}{r}\right] + q_B \ln\left[\frac{r}{D}\right] + q_C \ln\left[\frac{D}{D}\right]\right] \\ &= \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D}{r}\right] + q_B \ln\left[\frac{r}{D}\right]\right] \text{ (V)} \end{aligned} \tag{13.74}$$

$$\begin{aligned} V_{AC} &= \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D}{r}\right] + q_B \ln\left[\frac{D}{D}\right] + q_C \ln\left[\frac{r}{D}\right]\right] \\ &= \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D}{r}\right] + q_C \ln\left[\frac{r}{D}\right]\right] \text{ (V)} \end{aligned} \tag{13.75}$$

Balanced line-to-line voltages with sequence abc, expressed in terms of the line-to-neutral voltage are

$$V_{AB} = \sqrt{3}\, V_{AN} \angle 30^\circ \text{ and } V_{AC} = -V_{CA} = \sqrt{3}\, V_{AN} \angle -30^\circ;$$

where V_{AN} is the line-to-neutral voltage. Therefore, V_{AN} can be expressed in terms of V_{AB} and V_{AC} as

$$V_{AN} = \frac{V_{AB} + V_{AC}}{3} \tag{13.76}$$

and thus, substituting V_{AB} and V_{AC} from Eqs. (13.67) and (13.68) we have

$$\begin{aligned} V_{AN} &= \frac{1}{6\pi\varepsilon_0}\left[\left[q_A \ln\left[\frac{D}{r}\right] + q_B \ln\left[\frac{r}{D}\right]\right] + \left[q_A \ln\left[\frac{D}{r}\right] + q_C \ln\left[\frac{r}{D}\right]\right]\right] \\ &= \frac{1}{6\pi\varepsilon_0}\left[2q_A \ln\left[\frac{D}{r}\right] + \left(q_B + q_C\right) \ln\left[\frac{r}{D}\right]\right] \text{ (V)} \end{aligned} \tag{13.77}$$

Under balanced conditions $q_A + q_B + q_C = 0$, or $-q_A = (q_B + q_C)$ then, the final expression for the line-to-neutral voltage is

$$V_{AN} = \frac{1}{2\pi\varepsilon_0} q_A \ln\left[\frac{D}{r}\right] \text{ (V)} \tag{13.78}$$

The positive sequence capacitance per unit length between phase A and neutral can now be obtained. The same result is obtained for capacitance between phases B and C to neutral

$$C_{\mathrm{AN}} = \frac{q_{\mathrm{A}}}{V_{\mathrm{AN}}} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{D}{r}\right]} \ \ (\mathrm{F/m}) \tag{13.79}$$

13.5.4 Capacitance of Stranded Bundle Conductors

The calculation of the capacitance in the equation above is based on

1. Solid conductors with zero resistivity (zero internal electric field)
2. Charge uniformly distributed
3. Equilateral spacing of phase conductors

In actual transmission lines, the resistivity of the conductors produces a small internal electric field and therefore, the electric field at the conductor surface is smaller than the estimated. However, the difference is negligible for practical purposes.

Because of the presence of other charged conductors, the charge distribution is nonuniform, and therefore the estimated capacitance is different. However, this effect is negligible for most practical calculations. In a line with stranded conductors, the capacitance is evaluated assuming a solid conductor with the same radius as the outside radius of the stranded conductor. This produces a negligible difference.

Most transmission lines do not have equilateral spacing of phase conductors. This causes differences between the line-to-neutral capacitances of the three phases. However, transposing the phase conductors balances the system resulting in equal line-to-neutral capacitance for each phase and is developed in the following manner.

Consider a transposed three-phase line with conductors having the same radius r, and with space between conductors D_{AB}, D_{BC}, and D_{AC} , where D_{AB}, D_{BC}, and $D_{\mathrm{AC}} > r$.

Assuming abc positive sequence, the expressions for V_{AB} on the first, second, and third section of the transposed line are

$$V_{\mathrm{AB\ first}} = \frac{1}{2\pi\varepsilon_0}\left[q_{\mathrm{A}}\ln\left[\frac{D_{\mathrm{AB}}}{r}\right] + q_{\mathrm{B}}\ln\left[\frac{r}{D_{\mathrm{AB}}}\right] + q_{\mathrm{C}}\ln\left[\frac{D_{\mathrm{AB}}}{D_{\mathrm{AC}}}\right]\right] \ (\mathrm{V}) \tag{13.80}$$

$$V_{\mathrm{AB\ second}} = \frac{1}{2\pi\varepsilon_0}\left[q_{\mathrm{A}}\ln\left[\frac{D_{\mathrm{BC}}}{r}\right] + q_{\mathrm{B}}\ln\left[\frac{r}{D_{\mathrm{BC}}}\right] + q_{\mathrm{C}}\ln\left[\frac{D_{\mathrm{AC}}}{D_{\mathrm{AB}}}\right]\right] \ (\mathrm{V}) \tag{13.81}$$

$$V_{\mathrm{AB\ third}} = \frac{1}{2\pi\varepsilon_0}\left[q_{\mathrm{A}}\ln\left[\frac{D_{\mathrm{AC}}}{r}\right] + q_{\mathrm{B}}\ln\left[\frac{r}{D_{\mathrm{AC}}}\right] + q_{\mathrm{C}}\ln\left[\frac{D_{\mathrm{AB}}}{D_{\mathrm{BC}}}\right]\right] \ (\mathrm{V}) \tag{13.82}$$

Similarly, the expressions for V_{AC} on the first, second, and third section of the transposed line are

$$V_{\mathrm{AC\ first}} = \frac{1}{2\pi\varepsilon_0}\left[q_{\mathrm{A}}\ln\left[\frac{D_{\mathrm{AC}}}{r}\right] + q_{\mathrm{B}}\ln\left[\frac{D_{\mathrm{BC}}}{D_{\mathrm{AB}}}\right] + q_{\mathrm{C}}\ln\left[\frac{r}{D_{\mathrm{AC}}}\right]\right] \tag{13.83}$$

$$V_{\mathrm{AC\ second}} = \frac{1}{2\pi\varepsilon_0}\left[q_{\mathrm{A}}\ln\left[\frac{D_{\mathrm{AB}}}{r}\right] + q_{\mathrm{B}}\ln\left[\frac{D_{\mathrm{AC}}}{D_{\mathrm{BC}}}\right] + q_{\mathrm{C}}\ln\left[\frac{r}{D_{\mathrm{AB}}}\right]\right] \tag{13.84}$$

$$V_{\mathrm{AC\ third}} = \frac{1}{2\pi\varepsilon_0}\left[q_{\mathrm{A}}\ln\left[\frac{D_{\mathrm{BC}}}{r}\right] + q_{\mathrm{B}}\ln\left[\frac{D_{\mathrm{AB}}}{D_{\mathrm{AC}}}\right] + q_{\mathrm{C}}\ln\left[\frac{r}{D_{\mathrm{BC}}}\right]\right] \tag{13.85}$$

Taking the average value of the three sections, we have the final expressions of V_{AB} and V_{AC} in the transposed line

$$V_{\text{AB transp}} = \frac{V_{\text{AB first}} + V_{\text{AB second}} + V_{\text{AB third}}}{3}$$
$$= \frac{1}{6\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{AB}D_{AC}D_{BC}}{r^3}\right] + q_B \ln\left[\frac{r^3}{D_{AB}D_{AC}D_{BC}}\right] + q_C \ln\left[\frac{D_{AC}D_{AC}D_{BC}}{D_{AC}D_{AC}D_{BC}}\right]\right] \text{(V)} \quad (13.86)$$

$$V_{\text{AC transp}} = \frac{V_{\text{AC first}} + V_{\text{AC second}} + V_{\text{AC third}}}{3}$$
$$= \frac{1}{6\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{AB}D_{AC}D_{BC}}{r^3}\right] + q_B \ln\left[\frac{D_{AC}D_{AC}D_{BC}}{D_{AB}D_{AC}D_{BC}}\right] + q_C \ln\left[\frac{r^3}{D_{AC}D_{AC}D_{BC}}\right]\right] \text{(V)} \quad (13.87)$$

For a balanced system where $-q_A = (q_B + q_C)$, the phase-to-neutral voltage V_{AN} (phase voltage) is

$$V_{\text{AN transp}} = \frac{V_{\text{AB transp}} + V_{\text{AC transp}}}{3}$$
$$= \frac{1}{18\pi\varepsilon_0}\left[2\, q_A \ln\left[\frac{D_{AB}D_{AC}D_{BC}}{r^3}\right] + (q_B + q_C)\ln\left[\frac{r^3}{D_{AB}D_{AC}D_{BC}}\right]\right]$$
$$= \frac{1}{6\pi\varepsilon_0} q_A \ln\left[\frac{D_{AB}D_{AC}D_{BC}}{r^3}\right] = \frac{1}{2\pi\varepsilon_0} q_A \ln\left[\frac{\text{GMD}}{r}\right] \text{ (V)} \quad (13.88)$$

where $\text{GMD} = \sqrt[3]{D_{AB}D_{BC}D_{CA}}$ = geometrical mean distance for a three-phase line.

For bundle conductors, an equivalent radius r_e replaces the radius r of a single conductor and is determined by the number of conductors per bundle and the spacing of conductors. The expression of r_e is similar to $\text{GMR}_{\text{bundle}}$ used in the calculation of the inductance per phase, except that the actual outside radius of the conductor is used instead of the $\text{GMR}_{\text{phase}}$. Therefore, the expression for V_{AN} is

$$V_{\text{AN transp}} = \frac{1}{2\pi\varepsilon_0} q_A \ln\left[\frac{\text{GMD}}{r_e}\right] \text{ (V)} \quad (13.89)$$

where $r_e = (d^{n-1} r)^{1/n}$ = equivalent radius for up to three conductors per bundle (m)
$r_e = 1.09\ (d^3 r)^{1/4}$ = equivalent radius for four conductors per bundle (m)
d = distance between bundle conductors (m)
n = number of conductors per bundle

Finally, the capacitance and capacitive reactance, per unit length, from phase to neutral can be evaluated as

$$C_{\text{AN transp}} = \frac{q_A}{V_{\text{AN transp}}} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{\text{GMD}}{r_e}\right]} \text{ (F/m)} \quad (13.90)$$

$$X_{\text{AN transp}} = \frac{1}{2\pi f C_{\text{AN transp}}} = \frac{1}{4\pi f \varepsilon_0} \ln\left[\frac{\text{GMD}}{r_e}\right] \ (\Omega/\text{m}) \quad (13.91)$$

13.5.5 Capacitance Due to Earth's Surface

Considering a single-overhead conductor with a return path through the earth, separated a distance H from earth's surface, the charge of the earth would be equal in magnitude to that on the conductor but of opposite sign. If the earth is assumed as a perfectly conductive horizontal plane with infinite length, then the electric field lines will go from the conductor to the earth, perpendicular to the earth's surface (Fig. 13.17).

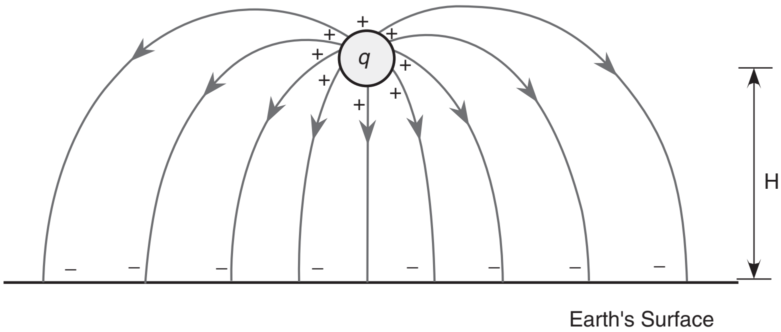

FIGURE 13.17 Distribution of electric field lines from an overhead conductor to earth's surface.

To calculate the capacitance, the negative charge of the earth can be replaced by an equivalent charge of an image conductor with the same radius as the overhead conductor, lying just below the overhead conductor (Fig. 13.18).

The same principle can be extended to calculate the capacitance per phase of a three-phase system. Figure 13.19 shows an equilateral arrangement of identical single conductors for phases A, B, and C carrying the charges q_A, q_B, and q_C and their respective image conductors A′, B′, and C′.

D_A, D_B, and D_C are perpendicular distances from phases A, B, and C to earth's surface. $D_{AA'}$, $D_{BB'}$, and $D_{CC'}$ are the perpendicular distances from phases A, B, and C to the image conductors A′, B′, and C′. Voltage V_{AB} can be obtained as

$$V_{AB} = \frac{1}{2\pi\varepsilon_0}\left[\begin{array}{l} q_A \ln\left[\dfrac{D_{AB}}{r_A}\right] + q_B \ln\left[\dfrac{r_B}{D_{AB}}\right] + q_C \ln\left[\dfrac{D_{BC}}{D_{AC}}\right] - \\ -q_A \ln\left[\dfrac{D_{AB'}}{D_{AA'}}\right] - q_B \ln\left[\dfrac{D_{BB'}}{D_{AB'}}\right] - q_C \ln\left[\dfrac{D_{BC'}}{D_{AC'}}\right] \end{array}\right] \text{(V)} \tag{13.92}$$

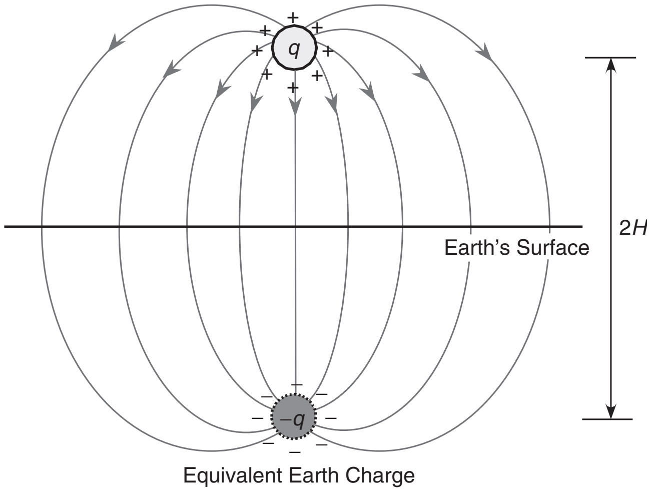

FIGURE 13.18 Equivalent image conductor representing the charge of the earth.

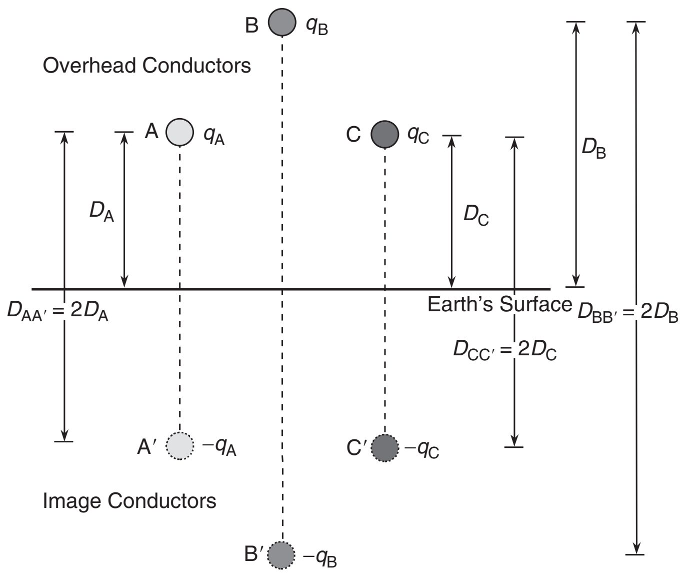

FIGURE 13.19 Arrangement of image conductors in a three-phase transmission line.

As overhead conductors are identical, then $r = r_A = r_B = r_C$. Also, as the conductors have equilateral arrangement, $D = D_{AB} = D_{BC} = D_{CA}$

$$V_{AB} = \frac{1}{2\pi\varepsilon_0}\left[q_A\left(\ln\left[\frac{D}{r}\right] - \ln\left[\frac{D_{AB'}}{D_{AA'}}\right]\right) + q_B\left(\ln\left[\frac{r}{D}\right] - \ln\left[\frac{D_{BB'}}{D_{AB'}}\right]\right) - q_C \ln\left[\frac{D_{BC'}}{D_{AC'}}\right]\right] \text{ (V)} \quad (13.93)$$

Similarly, expressions for V_{BC} and V_{AC} are

$$V_{BC} = \frac{1}{2\pi\varepsilon_0}\left[-q_A \ln\left[\frac{D_{CA'}}{D_{BA'}}\right] + q_B\left(\ln\left[\frac{D}{r}\right] - \ln\left[\frac{D_{CB'}}{D_{BB'}}\right]\right) + q_C\left(\ln\left[\frac{r}{D}\right] - \ln\left[\frac{D_{CC'}}{D_{BC'}}\right]\right)\right] \text{ (V)} \quad (13.94)$$

$$V_{AC} = \frac{1}{2\pi\varepsilon_0}\left[q_A\left(\ln\left[\frac{D}{r}\right] - \ln\left[\frac{D_{CA'}}{D_{AA'}}\right]\right) - q_B \ln\left[\frac{D_{CB'}}{D_{AB'}}\right] + q_C\left(\ln\left[\frac{r}{D}\right] - \ln\left[\frac{D_{CC'}}{D_{AC'}}\right]\right)\right] \text{ (V)} \quad (13.95)$$

The phase voltage V_{AN} becomes, through algebraic reduction,

$$V_{AN} = \frac{V_{AB} + V_{AC}}{3}$$
$$= \frac{1}{2\pi\varepsilon_0} q_A \left(\ln\left[\frac{D}{r}\right] - \ln\left[\frac{\sqrt[3]{D_{AB'}D_{BC'}D_{CA'}}}{\sqrt[3]{D_{AA'}D_{BB'}D_{CC'}}}\right]\right) \text{ (V)} \quad (13.96)$$

Therefore, the phase capacitance C_{AN}, per unit length, is

$$C_{AN} = \frac{q_A}{V_{AN}} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{D}{r}\right] - \ln\left[\frac{\sqrt[3]{D_{AB'}D_{BC'}D_{CA'}}}{\sqrt[3]{D_{AA'}D_{BB'}D_{CC'}}}\right]} \text{ (F/m)} \quad (13.97)$$

Equations (13.79) and (13.97) have similar expressions, except for the term $\ln\left((D_{AB'}\, D_{BC'}\, D_{CA'})^{1/3}/(D_{AA'}\, D_{BB'}\, D_{CC'})^{1/3}\right)$ included in Eq. (13.97). That term represents the effect of the earth on phase capacitance, increasing its total value. However, the capacitance increment is really small, and is usually

TABLE 13.2a Characteristics of Aluminum Cable Steel Reinforced Conductors (ACSR)

	Cross-Section Area				Diameter			Approx. Current-Carrying Capacity	Resistance (mΩ/km)					60 Hz Reactances (Dm = 1 m)	
		Aluminum								AC (60 Hz)					
Code	Total (mm^2)	(kcmil)	(mm^2)	Stranding Al/Steel	Conductor (mm)	Core (mm)	Layers	(Amperes)	DC 25°C	25°C	50°C	75°C	GMR (mm)	X_1 (Ω/km)	X_0 (MΩ/km)
–	1521	2 776	1407	84/19	50.80	13.87	4		21.0	24.5	26.2	28.1	20.33	0.294	0.175
Joree	1344	2 515	1274	76/19	47.75	10.80	4		22.7	26.0	28.0	30.0	18.93	0.299	0.178
Thrasher	1235	2 312	1171	76/19	45.77	10.34	4		24.7	27.7	30.0	32.2	18.14	0.302	0.180
Kiwi	1146	2 167	1098	72/7	44.07	8.81	4		26.4	29.4	31.9	34.2	17.37	0.306	0.182
Bluebird	1181	2 156	1092	84/19	44.75	12.19	4		26.5	29.0	31.4	33.8	17.92	0.303	0.181
Chukar	976	1 781	902	84/19	40.69	11.10	4		32.1	34.1	37.2	40.1	16.28	0.311	0.186
Falcon	908	1 590	806	54/19	39.24	13.08	3	1 380	35.9	37.4	40.8	44.3	15.91	0.312	0.187
Lapwing	862	1 590	806	45/7	38.20	9.95	3	1 370	36.7	38.7	42.1	45.6	15.15	0.316	0.189
Parrot	862	1 510	765	54/19	38.23	12.75	3	1 340	37.8	39.2	42.8	46.5	15.48	0.314	0.189
Nuthatch	818	1 510	765	45/7	37.21	9.30	3	1 340	38.7	40.5	44.2	47.9	14.78	0.318	0.190
Plover	817	1 431	725	54/19	37.21	12.42	3	1 300	39.9	41.2	45.1	48.9	15.06	0.316	0.190
Bobolink	775	1 431	725	45/7	36.25	9.07	3	1 300	35.1	42.6	46.4	50.3	14.39	0.320	0.191
Martin	772	1 351	685	54/19	36.17	12.07	3	1 250	42.3	43.5	47.5	51.6	14.63	0.319	0.191
Dipper	732	1 351	685	45/7	35.20	8.81	3	1 250	43.2	44.9	49.0	53.1	13.99	0.322	0.193
Pheasant	726	1 272	645	54/19	35.10	11.71	3	1 200	44.9	46.1	50.4	54.8	14.20	0.321	0.193
Bittern	689	1 272	644	45/7	34.16	8.53	3	1 200	45.9	47.5	51.9	56.3	13.56	0.324	0.194
Grackle	681	1 192	604	54/19	34.00	11.33	3	1 160	47.9	49.0	53.6	58.3	13.75	0.323	0.194
Bunting	646	1 193	604	45/7	33.07	8.28	3	1 160	48.9	50.4	55.1	59.9	13.14	0.327	0.196
Finch	636	1 114	564	54/19	32.84	10.95	3	1 110	51.3	52.3	57.3	62.3	13.29	0.326	0.196
Bluejay	603	1 113	564	45/7	31.95	8.00	3	1 110	52.4	53.8	58.9	64.0	12.68	0.329	0.197
Curlew	591	1 033	523	54/7	31.62	10.54	3	1 060	56.5	57.4	63.0	68.4	12.80	0.329	0.198

Ortolan	560	1 033	525	45/7	30.78	7.70	3	1 060	56.5	57.8	63.3	68.7	12.22	0.332	0.199
Merganser	596	954	483	30/7	31.70	13.60	2	1 010	61.3	61.8	67.9	73.9	13.11	0.327	0.198
Cardinal	546	954	483	54/7	30.38	10.13	3	1 010	61.2	62.0	68.0	74.0	12.31	0.332	0.200
Rail	517	954	483	45/7	29.59	7.39	3	1 010	61.2	62.4	68.3	74.3	11.73	0.335	0.201
Baldpate	562	900	456	30/7	30.78	13.21	2	960	65.0	65.5	71.8	78.2	12.71	0.329	0.199
Canary	515	900	456	54/7	29.51	9.83	3	970	64.8	65.5	72.0	78.3	11.95	0.334	0.201
Ruddy	478	900	456	45/7	28.73	7.19	3	970	64.8	66.0	72.3	78.6	11.40	0.337	0.202
Crane	501	875	443	54/7	29.11	9.70	3	950	66.7	67.5	74.0	80.5	11.80	0.335	0.202
Willet	474	874	443	45/7	28.32	7.09	3	950	66.7	67.9	74.3	80.9	11.25	0.338	0.203
Skimmer	479	795	403	30/7	29.00	12.40	2	940	73.5	74.0	81.2	88.4	11.95	0.334	0.202
Mallard	495	795	403	30/19	28.96	12.42	2	910	73.5	74.0	81.2	88.4	11.95	0.334	0.202
Drake	469	795	403	26/7	28.14	10.36	2	900	73.3	74.0	81.2	88.4	11.43	0.337	0.203
Condor	455	795	403	54/7	27.74	9.25	3	900	73.4	74.1	81.4	88.6	11.22	0.339	0.204
Cuckoo	455	795	403	24/7	27.74	9.25	2	900	73.4	74.1	81.4	88.5	11.16	0.339	0.204
Tern	431	795	403	45/7	27.00	6.76	3	900	73.4	74.4	81.6	88.8	10.73	0.342	0.205
Coot	414	795	403	36/1	26.42	3.78	3	910	73.0	74.4	81.5	88.6	10.27	0.345	0.206
Buteo	447	715	362	30/7	27.46	11.76	2	840	81.8	82.2	90.2	98.3	11.34	0.338	0.204
Redwing	445	715	362	30/19	27.46	11.76	2	840	81.8	82.2	90.2	98.3	11.34	0.338	0.204
Starling	422	716	363	26/7	26.7	9.82	2	840	81.5	82.1	90.1	98.1	10.82	0.341	0.206
Crow	409	715	362	54/7	26.31	8.76	3	840	81.5	82.2	90.2	98.2	10.67	0.342	0.206

Current capacity evaluated at 75°C conductor temperature, 25°C air temperature, wind speed of 1.4 mi/h, and frequency of 60 Hz.

Sources: *Transmission Line Reference Book 345 kV and Above*, 2nd ed., Electric Power Research Institute, Palo Alto, California, 1987. With permission.

Glover, J.D. and Sarma, M.S., *Power System Analysis and Design*, 3rd ed., Brooks/Cole, 2002. With permission.

TABLE 13.2b Characteristics of Aluminum Cable Steel Reinforced Conductors (ACSR)

Code	Cross-Section Area			Stranding	Diameter		Layers	Approx. Current-Carrying Capacity	Resistance (mΩ/km)				GMR	60 Hz Reactances (Dm = 1 m)	
	Total	Aluminum			Conductor	Core			DC	AC (60 Hz)				X_1	X_0
	(mm^2)	(kcmil)	(mm^2)	Al/Steel	(mm)	(mm)		(Amperes)	25°C	25°C	50°C	75°C	(mm)	(Ω/km)	(MΩ/km)
Stilt	410	716	363	24/7	26.31	8.76	2	840	81.5	82.2	90.2	98.1	10.58	0.343	0.206
Grebe	388	716	363	45/7	25.63	6.4	3	840	81.5	82.5	90.4	98.4	10.18	0.346	0.208
Gannet	393	666	338	26/7	25.76	9.5	2	800	87.6	88.1	96.6	105.3	10.45	0.344	0.208
Gull	382	667	338	54/7	25.4	8.46	3	800	87.5	88.1	96.8	105.3	10.27	0.345	0.208
Flamingo	382	667	338	24/7	25.4	8.46	2	800	87.4	88.1	96.7	105.3	10.21	0.346	0.208
Scoter	397	636	322	30/7	25.88	11.1	2	800	91.9	92.3	101.4	110.4	10.70	0.342	0.207
Egret	396	636	322	30/19	25.88	11.1	2	780	91.9	92.3	101.4	110.4	10.70	0.342	0.207
Grosbeak	375	636	322	26/7	25.15	9.27	2	780	91.7	92.2	101.2	110.3	10.21	0.346	0.209
Goose	364	636	322	54/7	24.82	8.28	3	770	91.8	92.4	101.4	110.4	10.06	0.347	0.208
Rook	363	636	322	24/7	24.82	8.28	2	770	91.7	92.3	101.3	110.3	10.06	0.347	0.209
Kingbird	340	636	322	18/1	23.88	4.78	2	780	91.2	92.2	101.1	110.0	9.27	0.353	0.211
Swirl	331	636	322	36/1	23.62	3.38	3	780	91.3	92.4	101.3	110.3	9.20	0.353	0.212
Wood Duck	378	605	307	30/7	25.25	10.82	2	760	96.7	97.0	106.5	116.1	10.42	0.344	0.208
Teal	376	605	307	30/19	25.25	10.82	2	770	96.7	97.0	106.5	116.1	10.42	0.344	0.208
Squab	356	605	356	26/7	25.54	9.04	2	760	96.5	97.0	106.5	116.0	9.97	0.347	0.208
Peacock	346	605	307	24/7	24.21	8.08	2	760	96.4	97.0	106.4	115.9	9.72	0.349	0.210
Duck	347	606	307	54/7	24.21	8.08	3	750	96.3	97.0	106.3	115.8	9.81	0.349	0.210
Eagle	348	557	282	30/7	24.21	10.39	2	730	105.1	105.4	115.8	126.1	10.00	0.347	0.210
Dove	328	556	282	26/7	23.55	8.66	2	730	104.9	105.3	115.6	125.9	9.54	0.351	0.212
Parakeet	319	557	282	24/7	23.22	7.75	2	730	104.8	105.3	115.6	125.9	9.33	0.352	0.212

Osprey	298	556	282	18/1	22.33	4.47	2	740	104.4	105.2	115.4	125.7	8.66	0.358	0.214
Hen	298	477	242	30/7	22.43	9.6	2	670	122.6	122.9	134.9	147.0	9.27	0.353	0.214
Hawk	281	477	242	26/7	21.79	8.03	2	670	122.4	122.7	134.8	146.9	8.84	0.357	0.215
Flicker	273	477	273	24/7	21.49	7.16	2	670	122.2	122.7	134.7	146.8	8.63	0.358	0.216
Pelican	255	477	242	18/1	20.68	4.14	2	680	121.7	122.4	134.4	146.4	8.02	0.364	0.218
Lark	248	397	201	30/7	20.47	8.76	2	600	147.2	147.4	161.9	176.4	8.44	0.360	0.218
Ibis	234	397	201	26/7	19.89	7.32	2	590	146.9	147.2	161.7	176.1	8.08	0.363	0.220
Brant	228	398	201	24/7	19.61	6.53	2	590	146.7	147.1	161.6	176.1	7.89	0.365	0.221
Chickadee	213	397	201	18/1	18.87	3.78	2	590	146.1	146.7	161.0	175.4	7.32	0.371	0.222
Oriole	210	336	170	30/7	18.82	8.08	2	530	173.8	174.0	191.2	208.3	7.77	0.366	0.222
Linnet	198	336	170	26/7	18.29	6.73	2	530	173.6	173.8	190.9	208.1	7.41	0.370	0.224
Widgeon	193	336	170	24/7	18.03	6.02	2	530	173.4	173.7	190.8	207.9	7.25	0.371	0.225
Merlin	180	336	170	18/1	16.46	3.48	2	530	173.0	173.1	190.1	207.1	6.74	0.377	0.220
Piper	187	300	152	30/7	17.78	7.62	2	500	195.0	195.1	214.4	233.6	7.35	0.370	0.225
Ostrich	177	300	152	26/7	17.27	6.38	2	490	194.5	194.8	214.0	233.1	7.01	0.374	0.227
Gadwall	172	300	152	24/7	17.04	5.69	2	490	194.5	194.8	213.9	233.1	6.86	0.376	0.227
Phoebe	160	300	152	18/1	16.41	3.28	2	490	193.5	194.0	213.1	232.1	6.37	0.381	0.229
Junco	167	267	135	30/7	16.76	7.19	2	570	219.2	219.4	241.1	262.6	6.92	0.375	0.228
Partridge	157	267	135	26/7	16.31	5.99	2	460	218.6	218.9	240.5	262.0	6.61	0.378	0.229
Waxwing	143	267	135	18/1	15.47	3.1	2	460	217.8	218.1	239.7	261.1	6.00	0.386	0.232

Current capacity evaluated at 75°C conductor temperature, 25°C air temperature, wind speed of 1.4 mi/h, and frequency of 60 Hz.

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TABLE 13.3a Characteristics of All-Aluminum-Conductors (AAC)

	Cross-Section Area			Diameter		Approx. Current-Carrying Capacity	Resistance (mΩ/km)					60 Hz Reactances (Dm = 1 m)	
								AC (60 Hz)					
Code	(mm^2)	kcmil or AWG	Stranding	(mm)	Layers	(Amperes)	DC 25°C	25°C	50°C	75°C	GMR (mm)	X_L (Ω/km)	X_C (MΩ/km)
Coreopsis	806.2	1591	61	36.93	4	1380	36.5	39.5	42.9	46.3	14.26	0.320	0.190
Glaldiolus	765.8	1511	61	35.99	4	1340	38.4	41.3	44.9	48.5	13.90	0.322	0.192
Carnation	725.4	1432	61	35.03	4	1300	40.5	43.3	47.1	50.9	13.53	0.324	0.193
Columbine	865.3	1352	61	34.04	4	1250	42.9	45.6	49.6	53.6	13.14	0.327	0.196
Narcissus	644.5	1272	61	33.02	4	1200	45.5	48.1	52.5	56.7	12.74	0.329	0.194
Hawthorn	604.1	1192	61	31.95	4	1160	48.7	51.0	55.6	60.3	12.34	0.331	0.197
Marigold	564.2	1113	61	30.89	4	1110	52.1	54.3	59.3	64.3	11.92	0.334	0.199
Larkspur	524	1034	61	29.77	4	1060	56.1	58.2	63.6	69.0	11.49	0.337	0.201
Bluebell	524.1	1034	37	29.71	3	1060	56.1	58.2	63.5	68.9	11.40	0.337	0.201
Goldenrod	483.7	955	61	28.6	4	1010	60.8	62.7	68.6	74.4	11.03	0.340	0.203
Magnolia	483.6	954	37	28.55	3	1010	60.8	62.7	68.6	74.5	10.97	0.340	0.203
Crocus	443.6	875	61	27.38	4	950	66.3	68.1	74.5	80.9	10.58	0.343	0.205
Anemone	443.5	875	37	27.36	3	950	66.3	68.1	74.5	80.9	10.49	0.344	0.205
Lilac	403.1	796	61	26.11	4	900	73.0	74.6	81.7	88.6	10.09	0.347	0.207
Arbutus	402.9	795	37	26.06	3	900	73.0	74.6	81.7	88.6	10.00	0.347	0.207
Nasturtium	362.5	715	61	24.76	4	840	81.2	82.6	90.5	98.4	9.57	0.351	0.209
Violet	362.8	716	37	24.74	3	840	81.1	82.5	90.4	98.3	9.48	0.351	0.209
Orchid	322.2	636	37	23.32	3	780	91.3	92.6	101.5	110.4	8.96	0.356	0.212
Mistletoe	281.8	556	37	21.79	3	730	104.4	105.5	115.8	126.0	8.38	0.361	0.215
Dahlia	281.8	556	19	21.72	2	730	104.4	105.5	115.8	125.9	8.23	0.362	0.216
Syringa	241.5	477	37	20.19	3	670	121.8	122.7	134.7	146.7	7.74	0.367	0.219
Cosmos	241.9	477	19	20.14	2	670	121.6	122.6	134.5	146.5	7.62	0.368	0.219
Canna	201.6	398	19	18.36	2	600	145.9	146.7	161.1	175.5	6.95	0.375	0.224
Tulip	170.6	337	19	16.92	2	530	172.5	173.2	190.1	207.1	6.40	0.381	0.228
Laurel	135.2	267	19	15.06	2	460	217.6	218.1	239.6	261.0	5.70	0.390	0.233
Daisy	135.3	267	7	14.88	1	460	217.5	218	239.4	260.8	5.39	0.394	0.233
Oxlip	107.3	212 or (4/0)	7	13.26	1	340	274.3	274.7	301.7	328.8	4.82	0.402	0.239
Phlox	85	168 or (3/0)	7	11.79	1	300	346.4	346.4	380.6	414.7	4.27	0.411	0.245
Aster	67.5	133 or (2/0)	7	10.52	1	270	436.1	439.5	479.4	522.5	3.81	0.40	0.25
Poppy	53.5	106 or (1/0)	7	9.35	1	230	550	550.2	604.5	658.8	3.38	0.429	0.256
Pansy	42.4	#1 AWG	7	8.33	1	200	694.2	694.2	763.2	831.6	3.02	0.438	0.261
Iris	33.6	#2 AWG	7	7.42	1	180	874.5	874.5	960.8	1047.9	2.68	0.446	0.267
Rose	21.1	#3 AWG	7	5.89	1	160	1391.5	1391.5	1528.9	1666.3	2.13	0.464	0.278
Peachbell	13.3	#4 AWG	7	4.67	1	140	2214.4	2214.4	2443.2	2652	1.71	0.481	0.289

Current capacity evaluated at 75°C conductor temperature, 25°C air temperature, wind speed of 1.4 mi/h, and frequency of 60 Hz.

Sources: *Transmission Line Reference Book 345 kV and Above*, 2nd ed., Electric Power Research Institute, Palo Alto, California, 1987. With permission.

Glover, J.D. and Sarma, M.S., *Power System Analysis and Design*, 3rd ed., Brooks/Cole, 2002. With permission.

TABLE 13.3b Characteristics of All-Aluminum-Conductors (AAC)

Code	Cross-Section Area (mm^2)	Cross-Section Area kcmil or AWG	Stranding	Diameter (mm)	Layers	Approx. Current-Carrying Capacity (Amperes)	Resistance (mΩ/km) DC 25°C	Resistance AC (60 Hz) 25°C	Resistance AC (60 Hz) 50°C	Resistance AC (60 Hz) 75°C	GMR (mm)	60 Hz Reactances (Dm = 1 m) X_L (Ω/km)	60 Hz Reactances (Dm = 1 m) X_C (MΩ/km)
EVEN SIZES													
Bluebonnet	1773.3	3500	7	54.81	6		16.9	22.2	23.6	25.0	21.24	0.290	0.172
Trillium	1520.2	3000	127	50.75	6		19.7	24.6	26.2	27.9	19.69	0.296	0.175
Lupine	1266.0	2499	91	46.30	5		23.5	27.8	29.8	31.9	17.92	0.303	0.180
Cowslip	1012.7	1999	91	41.40	5		29.0	32.7	35.3	38.0	16.03	0.312	0.185
Jessamine	887.0	1750	61	38.74	4		33.2	36.5	39.5	42.5	14.94	0.317	0.188
Hawkweed	506.7	1000	37	29.24	3	1030	58.0	60.0	65.5	71.2	11.22	0.339	0.201
Camelia	506.4	999	61	29.26	4	1030	58.1	60.1	65.5	71.2	11.31	0.338	0.201
Snapdragon	456.3	900	61	27.79	4	970	64.4	66.3	72.5	78.7	10.73	0.342	0.204
Cockscomb	456.3	900	37	27.74	3	970	64.4	66.3	72.5	78.7	10.64	0.343	0.204
Cattail	380.1	750	61	25.35	4	870	77.4	78.9	86.4	93.9	9.78	0.349	0.208
Petunia	380.2	750	37	23.85	3	870	77.4	78.9	86.4	93.9	9.72	0.349	0.208
Flag	354.5	700	61	24.49	4	810	83.0	84.4	92.5	100.6	9.45	0.352	0.210
Verbena	354.5	700	37	24.43	3	810	83.0	84.4	92.5	100.6	9.39	0.352	0.210
Meadowsweet	303.8	600	37	2.63	3	740	96.8	98.0	107.5	117.0	8.69	0.358	0.214
Hyacinth	253.1	500	37	20.65	3	690	116.2	117.2	128.5	140.0	7.92	0.365	0.218
Zinnia	253.3	500	19	20.60	2	690	116.2	117.2	128.5	139.9	7.80	0.366	0.218
Goldentuft	228.0	450	19	19.53	2	640	129.0	129.9	142.6	155.3	7.41	0.370	0.221
Daffodil	177.3	350	19	17.25	2	580	165.9	166.6	183.0	199.3	6.52	0.379	0.227
Peony	152.1	300	19	15.98	2	490	193.4	194.0	213.1	232.1	6.04	0.385	0.230
Valerian	126.7	250	19	14.55	2	420	232.3	232.8	255.6	278.6	5.52	0.392	0.235
Sneezewort	126.7	250	7	14.40	1	420	232.2	232.7	255.6	278.4	5.21	0.396	0.235

Current capacity evaluated at 75°C conductor temperature, 25°C air temperature, wind speed of 1.4 mi/h, and frequency of 60 Hz.

Sources: *Transmission Line Reference Book 345 kV and Above*, 2nd ed., Electric Power Research Institute, Palo Alto, California, 1987. With permission.

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neglected, because distances from overhead conductors to ground are always greater than distances among conductors.

13.6 Characteristics of Overhead Conductors

Tables 13.2a and 13.2b present typical values of resistance, inductive reactance and capacitance reactance, per unit length, of ACSR conductors. The size of the conductors (cross-section area) is specified in square millimeters and kcmil, where a cmil is the cross-section area of a circular conductor with a diameter of 1/1000 in. The tables include also the approximate current-carrying capacity of the conductors assuming 60 Hz, wind speed of 1.4 mi/h, and conductor and air temperatures of 75°C and 25°C, respectively. Tables 13.3a and 13.3b present the corresponding characteristics of AACs.

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14

Sag and Tension of Conductor

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The energized conductors of transmission and distribution lines must be placed to totally eliminate the possibility of injury to people. Overhead conductors, however, elongate with time, temperature, and tension, thereby changing their original positions after installation. Despite the effects of weather and loading on a line, the conductors must remain at safe distances from buildings, objects, and people or vehicles passing beneath the line at all times. To ensure this safety, the shape of the terrain along the right-of-way, the height and lateral position of the conductor support points, and the position of the conductor between support points under all wind, ice, and temperature conditions must be known.

Bare overhead transmission or distribution conductors are typically quite flexible and uniform in weight along their length. Because of these characteristics, they take the form of a catenary (Ehrenberg, 1935; Winkelmann, 1959) between support points. The shape of the catenary changes with conductor temperature, ice and wind loading, and time. To ensure adequate vertical and horizontal clearance under all weather and electrical loadings, and to ensure that the breaking strength of the conductor is not exceeded, the behavior of the conductor catenary under all conditions must be known before the line is designed. The future behavior of the conductor is determined through calculations commonly referred to as sag-tension calculations.

Sag-tension calculations predict the behavior of conductors based on recommended tension limits under varying loading conditions. These tension limits specify certain percentages of the conductor's rated breaking strength that are not to be exceeded upon installation or during the life of the line. These conditions, along with the elastic and permanent elongation properties of the conductor, provide the basis for determinating the amount of resulting sag during installation and long-term operation of the line.

Accurately determined initial sag limits are essential in the line design process. Final sags and tensions depend on initial installed sags and tensions and on proper handling during installation. The final sag shape of conductors is used to select support point heights and span lengths so that the minimum clearances will be maintained over the life of the line. If the conductor is damaged or the initial sags are incorrect, the line clearances may be violated or the conductor may break during heavy ice or wind loadings.

14.1 Catenary Cables

A bare-stranded overhead conductor is normally held clear of objects, people, and other conductors by periodic attachment to insulators. The elevation differences between the supporting structures affect the shape of the conductor catenary. The catenary's shape has a distinct effect on the sag and tension of the conductor, and therefore, must be determined using well-defined mathematical equations.

14.1.1 Level Spans

The shape of a catenary is a function of the conductor weight per unit length, *w*, the horizontal component of tension, *H*, span length, *S*, and the maximum sag of the conductor, *D*. Conductor sag and span length are illustrated in Fig. 14.1 for a level span.

The exact catenary equation uses hyperbolic functions. Relative to the low point of the catenary curve shown in Fig. 14.1, the height of the conductor, $y(x)$, above this low point is given by the following equation:

$$y(x) = \frac{H}{w} \cosh\left(\left(\frac{w}{H}x\right) - 1\right) = \frac{w(x^2)}{2H} \tag{14.1}$$

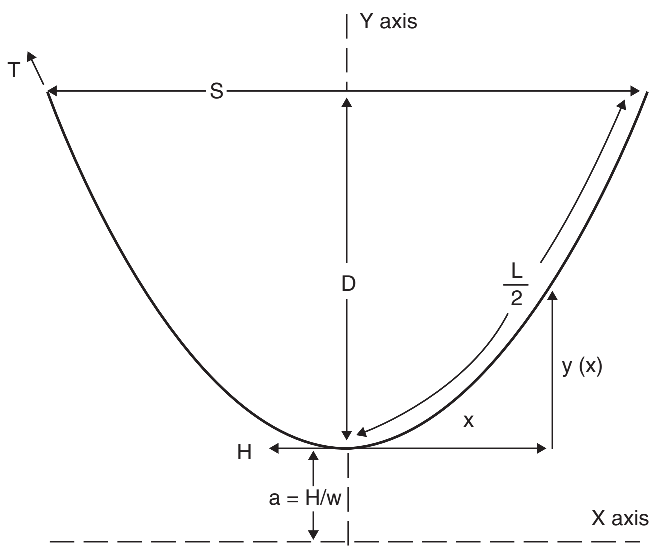


FIGURE 14.1 The catenary curve for level spans.

Note that x is positive in either direction from the low point of the catenary. The expression to the right is an approximate parabolic equation based upon a MacLaurin expansion of the hyperbolic cosine.

For a level span, the low point is in the center, and the sag, D, is found by substituting $x = S/2$ in the preceding equations. The exact and approximate parabolic equations for sag become the following:

$$D = \frac{H}{w}\left(\cosh\left(\frac{wS}{2H}\right) - 1\right) = \frac{w(S^2)}{8H} \tag{14.2}$$

The ratio, H/w, which appears in all of the preceding equations, is commonly referred to as the catenary constant. An increase in the catenary constant, having the units of length, causes the catenary curve to become shallower and the sag to decrease. Although it varies with conductor temperature, ice and wind loading, and time, the catenary constant typically has a value in the range of several thousand feet for most transmission-line catenaries.

The approximate or parabolic expression is sufficiently accurate as long as the sag is less than 5% of the span length. As an example, consider a 1000-ft span of Drake conductor ($w = 1.096$ lb/ft) installed at a tension of 4500 lb. The catenary constant equals 4106 ft. The calculated sag is 30.48 ft and 30.44 ft using the hyperbolic and approximate equations, respectively. Both estimates indicate a sag-to-span ratio of 3.4% and a sag difference of only 0.5 in.

The horizontal component of tension, H, is equal to the conductor tension at the point in the catenary where the conductor slope is horizontal. For a level span, this is the midpoint of the span length. At the ends of the level span, the conductor tension, T, is equal to the horizontal component plus the conductor weight per unit length, w, multiplied by the sag, D, as shown in the following:

$$T = H + wD \tag{14.3}$$

Given the conditions in the preceding example calculation for a 1000-ft level span of Drake ACSR, the tension at the attachment points exceeds the horizontal component of tension by 33 lb. It is common to perform sag-tension calculations using the horizontal tension component, but the average of the horizontal and support point tension is usually listed in the output.

14.1.2 Conductor Length

Application of calculus to the catenary equation allows the calculation of the conductor length, $L(x)$, measured along the conductor from the low point of the catenary in either direction.

The resulting equation becomes:

$$L(x) = \frac{H}{w}\mathrm{SINH}\left(\frac{wx}{H}\right) = x\left(1 + \frac{x^2(w^2)}{6H^2}\right) \tag{14.4}$$

For a level span, the conductor length corresponding to $x = S/2$ is half of the total conductor length and the total length, L, is:

$$L = \left(\frac{2H}{w}\right)\mathrm{SINH}\left(\frac{Sw}{2H}\right) = S\left(1 + \frac{S^2(w^2)}{24H^2}\right) \tag{14.5}$$

The parabolic equation for conductor length can also be expressed as a function of sag, D, by substitution of the sag parabolic equation, giving:

$$L = S + \frac{8D^2}{3S} \tag{14.6}$$

14.1.3 Conductor Slack

The difference between the conductor length, L, and the span length, S, is called slack. The parabolic equations for slack may be found by combining the preceding parabolic equations for conductor length, L, and sag, D:

$$L - S = S^3\left(\frac{w^2}{24H^2}\right) = D^2\left(\frac{8}{3S}\right) \tag{14.7}$$

While slack has units of length, it is often expressed as the percentage of slack relative to the span length. Note that slack is related to the cube of span length for a given H/w ratio and to the square of sag for a given span. For a series of spans having the same H/w ratio, the total slack is largely determined by the longest spans. It is for this reason that the ruling span is nearly equal to the longest span rather than the average span in a series of suspension spans.

Equation (14.7) can be inverted to obtain a more interesting relationship showing the dependence of sag, D, upon slack, L-S:

$$D = \sqrt{\frac{3S(L - S)}{8}} \tag{14.8}$$

As can be seen from the preceding equation, small changes in slack typically yield large changes in conductor sag.

14.1.4 Inclined Spans

Inclined spans may be analyzed using essentially the same equations that were used for level spans. The catenary equation for the conductor height above the low point in the span is the same. However, the span is considered to consist of two separate sections, one to the right of the low point and the other to the left as shown in Fig. 14.2 (Winkelmann, 1959). The shape of the catenary relative to the low point is unaffected by the difference in suspension point elevation (span inclination).

In each direction from the low point, the conductor elevation, y(x), relative to the low point is given by:

$$y(x) = \frac{H}{w}\cosh\left(\left(\frac{w}{H}x\right) - 1\right) = \frac{w(x^2)}{2H} \tag{14.9}$$

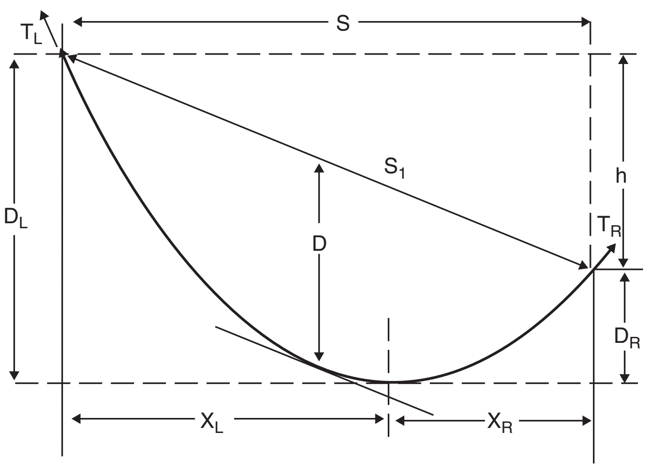


FIGURE 14.2 Inclined catenary span.

Note that x is considered positive in either direction from the low point.

The horizontal distance, x_L, from the left support point to the low point in the catenary is:

$$x_L = \frac{S}{2}\left(1 + \frac{h}{4D}\right) \tag{14.10}$$

The horizontal distance, x_R, from the right support point to the low point of the catenary is:

$$x_R = \frac{S}{2}\left(1 - \frac{h}{4D}\right) \tag{14.11}$$

where S = horizontal distance between support points.
h = vertical distance between support points.
S_l = straight-line distance between support points.
D = sag measured vertically from a line through the points of conductor support to a line tangent to the conductor.

The midpoint sag, D, is approximately equal to the sag in a horizontal span equal in length to the inclined span, S_l.

Knowing the horizonal distance from the low point to the support point in each direction, the preceding equations for $y(x)$, L, D, and T can be applied to each side of the inclined span.

The total conductor length, L, in the inclined span is equal to the sum of the lengths in the x_R and x_L sub-span sections:

$$L = S + \left(x_R^3 + x_L^3\right)\left(\frac{w^2}{6H^2}\right) \tag{14.12}$$

In each sub-span, the sag is relative to the corresponding support point elevation:

$$D_R = \frac{wx_R^2}{2H} \quad D_L = \frac{wx_L^2}{2H} \tag{14.13}$$

or in terms of sag, D, and the vertical distance between support points:

$$D_R = D\left(1 - \frac{h}{4D}\right)^2 \quad D_L = D\left(1 + \frac{h}{4D}\right)^2 \tag{14.14}$$

and the maximum tension is:

$$T_R = H + wD_R \quad T_L = H + wD_L \tag{14.15}$$

or in terms of upper and lower support points:

$$T_u = T_l + wh \tag{14.16}$$

where D_R = sag in right sub-span section
D_L = sag in left sub-span section
T_R = tension in right sub-span section
T_L = tension in left sub-span section
T_u = tension in conductor at upper support
T_l = tension in conductor at lower support

The horizontal conductor tension is equal at both supports. The vertical component of conductor tension is greater at the upper support and the resultant tension, T_u, is also greater.

14.1.5 Ice and Wind Conductor Loads

When a conductor is covered with ice and/or is exposed to wind, the effective conductor weight per unit length increases. During occasions of heavy ice and/or wind load, the conductor catenary tension increases dramatically along with the loads on angle and deadend structures. Both the conductor and its supports can fail unless these high-tension conditions are considered in the line design.

The National Electric Safety Code (NESC) suggests certain combinations of ice and wind corresponding to heavy, medium, and light loading regions of the United States. Figure 14.3 is a map of the U.S. indicating those areas (NESC, 1993). The combinations of ice and wind corresponding to loading region are listed in Table 14.1.

The NESC also suggests that increased conductor loads due to high wind loads without ice be considered. Figure 14.4 shows the suggested wind pressure as a function of geographical area for the United States (ASCE Std 7–88).

Certain utilities in very heavy ice areas use glaze ice thicknesses of as much as two inches to calculate iced conductor weight. Similarly, utilities in regions where hurricane winds occur may use wind loads as high as 34 lb/ft^2.

As the NESC indicates, the degree of ice and wind loads varies with the region. Some areas may have heavy icing, whereas some areas may have extremely high winds. The loads must be accounted for in the line design process so they do not have a detrimental effect on the line. Some of the effects of both the individual and combined components of ice and wind loads are discussed in the following.

14.1.5.1 Ice Loading

The formation of ice on overhead conductors may take several physical forms (glaze ice, rime ice, or wet snow). The impact of lower density ice formation is usually considered in the design of line sections at high altitudes.

The formation of ice on overhead conductors has the following influence on line design:

- Ice loads determine the maximum vertical conductor loads that structures and foundations must withstand.
- In combination with simultaneous wind loads, ice loads also determine the maximum transverse loads on structures.

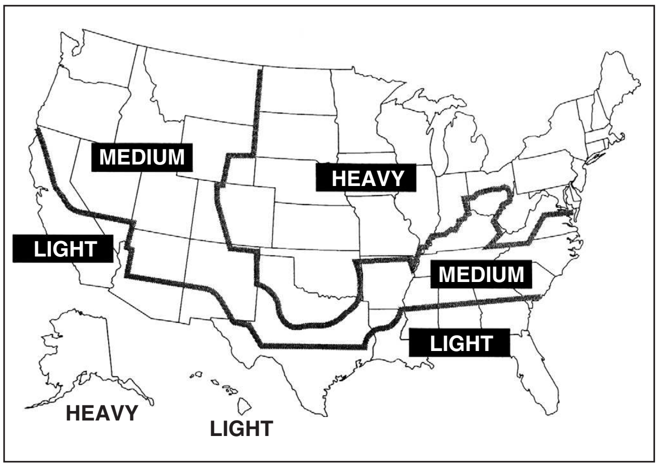


FIGURE 14.3 Ice and wind load areas of the U.S.

TABLE 14.1 Definitions of Ice and Wind Load for NESC Loading Areas

	Loading Districts			
	Heavy	Medium	Light	Extreme Wind Loading
Radial thickness of ice				
(in.)	0.50	0.25	0	0
(mm)	12.5	6.5	0	0
Horizontal wind pressure				
(lb/ft^2)	4	4	9	See Fig. 14.4
(Pa)	190	190	430	
Temperature				
(°F)	0	+15	+30	+60
(°C)	−20	−10	−1	+15
Constant to be added to the resultant for all conductors				
(lb/ft)	0.30	0.20	0.05	0.0
(N/m)	4.40	2.50	0.70	0.0

- In regions of heavy ice loads, the maximum sags and the permanent increase in sag with time (difference between initial and final sags) may be due to ice loadings.

Ice loads for use in designing lines are normally derived on the basis of past experience, code requirements, state regulations, and analysis of historical weather data. Mean recurrence intervals for heavy ice loadings are a function of local conditions along various routings. The impact of varying assumptions concerning ice loading can be investigated with line design software.

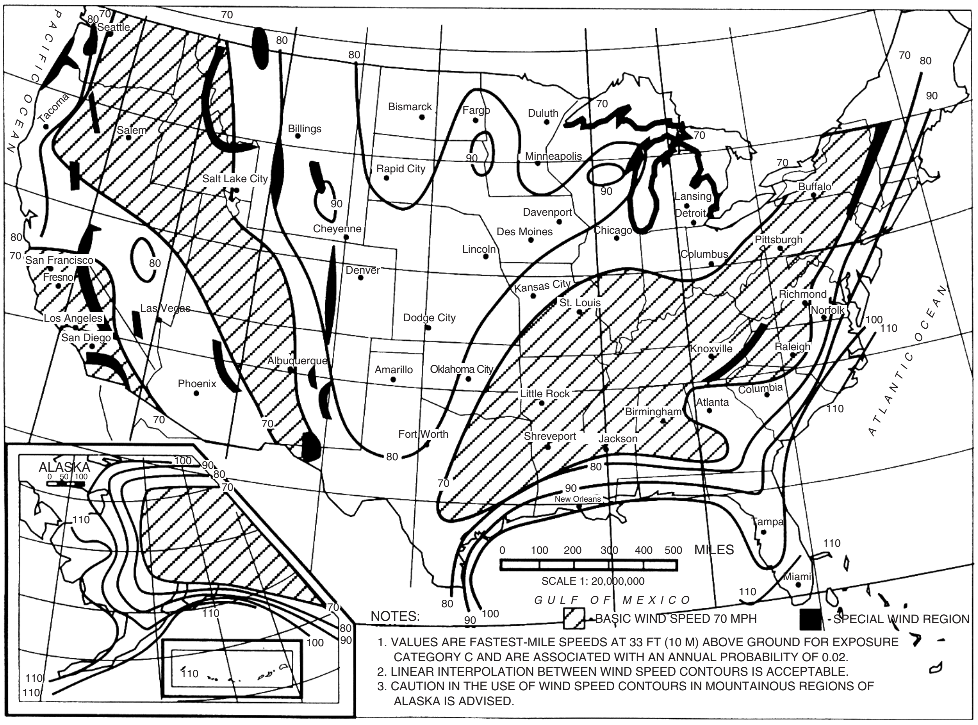


FIGURE 14.4 Wind pressure design values in the United States. Maximum recorded wind speed in miles/hour. (From Overend, P.R. and Smith, S., *Impulse Time Method of Sag Measurement*, American Society of Civil Engineers. With permission.)

TABLE 14.2 Ratio of Iced to Bare Conductor Weight

ACSR Conductor	D_c, in.	W_{bare}, lb/ft	W_{ice}, lb/ft	$\frac{W_{bare} + W_{ice}}{W_{bare}}$
#1/0 AWG -6/1 "Raven"	0.398	0.1451	0.559	4.8
477 kcmil-26/7 "Hawk"	0.858	0.6553	0.845	2.3
1590 kcmil-54/19 "Falcon"	1.545	2.042	1.272	1.6

The calculation of ice loads on conductors is normally done with an assumed glaze ice density of 57 lb/ft^3. The weight of ice per unit length is calculated with the following equation:

$$w_{\text{ice}} = 1.244t(D_c + t) \tag{14.17}$$

where t = thickness of ice, in.
D_c = conductor outside diameter, in.
w_{ice} = resultant weight of ice, lb/ft

The ratio of iced weight to bare weight depends strongly upon conductor diameter. As shown in Table 14.2 for three different conductors covered with 0.5-in radial glaze ice, this ratio ranges from 4.8 for #1/0 AWG to 1.6 for 1590-kcmil conductors. As a result, small diameter conductors may need to have a higher elastic modulus and higher tensile strength than large conductors in heavy ice and wind loading areas to limit sag.

14.1.5.2 Wind Loading

Wind loadings on overhead conductors influence line design in a number of ways:

- The maximum span between structures may be determined by the need for horizontal clearance to edge of right-of-way during moderate winds.
- The maximum transverse loads for tangent and small angle suspension structures are often determined by infrequent high wind-speed loadings.
- Permanent increases in conductor sag may be determined by wind loading in areas of light ice load.

Wind pressure load on conductors, P_w, is commonly specified in lb/ft^2. The relationship between P_w and wind velocity is given by the following equation:

$$P_w = 0.0025(V_w)^2 \tag{14.18}$$

where V_w = the wind speed in miles per hour.

The wind load per unit length of conductor is equal to the wind pressure load, P_w, multiplied by the conductor diameter (including radial ice of thickness t, if any), is given by the following equation:

$$W_w = P_w \frac{(D_c + 2t)}{12} \tag{14.19}$$

14.1.5.3 Combined Ice and Wind Loading

If the conductor weight is to include both ice and wind loading, the resultant magnitude of the loads must be determined vectorially. The weight of a conductor under both ice and wind loading is given by the following equation:

$$w_{w+i} = \sqrt{(w_b + w_i)^2 + (W_w)^2} \tag{14.20}$$

where w_b = bare conductor weight per unit length, lb/ft
w_i = weight of ice per unit length, lb/ft
w_w = wind load per unit length, lb/ft
$w_{w \pm i}$ = resultant of ice and wind loads, lb/ft

The NESC prescribes a safety factor, K, in pounds per foot, dependent upon loading district, to be added to the resultant ice and wind loading when performing sag and tension calculations. Therefore, the total resultant conductor weight, w, is:

$$w = w_{w+i} + K \tag{14.21}$$

14.1.6 Conductor Tension Limits

The NESC recommends limits on the tension of bare overhead conductors as a percentage of the conductor's rated breaking strength. The tension limits are: 60% under maximum ice and wind load, 33.3% initial unloaded (when installed) at 60°F, and 25% final unloaded (after maximum loading has occurred) at 60°F. It is common, however, for lower unloaded tension limits to be used. Except in areas experiencing severe ice loading, it is not unusual to find tension limits of 60% maximum, 25% unloaded initial, and 15% unloaded final. This set of specifications could easily result in an actual maximum tension on the order of only 35 to 40%, an initial tension of 20% and a final unloaded tension level of 15%. In this case, the 15% tension limit is said to govern.

Transmission-line conductors are normally not covered with ice, and winds on the conductor are usually much lower than those used in maximum load calculations. Under such everyday conditions, tension limits are specified to limit aeolian vibration to safe levels. Even with everyday lower tension levels of 15 to 20%, it is assumed that vibration control devices will be used in those sections of the line that are subject to severe vibration. Aeolian vibration levels, and thus appropriate unloaded tension limits, vary with the type of conductor, the terrain, span length, and the use of dampers. Special conductors, such as ACSS, SDC, and VR, exhibit high self-damping properties and may be installed to the full code limits, if desired.

14.2 Approximate Sag-Tension Calculations

Sag-tension calculations, using exacting equations, are usually performed with the aid of a computer; however, with certain simplifications, these calculations can be made with a handheld calculator. The latter approach allows greater insight into the calculation of sags and tensions than is possible with complex computer programs. Equations suitable for such calculations, as presented in the preceding section, can be applied to the following example:

It is desired to calculate the sag and slack for a 600-ft level span of 795 kcmil-26/7 ACSR "Drake" conductor. The bare conductor weight per unit length, w_b, is 1.094 lb/ft. The conductor is installed with a horizontal tension component, H, of 6300 lb, equal to 20% of its rated breaking strength of 31,500 lb.

By use of Eq. (14.2), the sag for this level span is:

$$D = \frac{1.094(600^2)}{(8)6300} = 7.81 \text{ ft } (2.38 \text{ m})$$

The length of the conductor between the support points is determined using Eq. (14.6):

$$L = 600 + \frac{8(7.81)^2}{3(600)} = 600.27 \text{ ft } (182.96 \text{ m})$$

Note that the conductor length depends solely on span and sag. It is not directly dependent on conductor tension, weight, or temperature. The conductor slack is the conductor length minus the span length; in this example, it is 0.27 ft (0.0826 m).

14.2.1 Sag Change with Thermal Elongation

ACSR and AAC conductors elongate with increasing conductor temperature. The rate of linear thermal expansion for the composite ACSR conductor is less than that of the AAC conductor because the steel strands in the ACSR elongate at approximately half the rate of aluminum. The effective linear thermal expansion coefficient of a non-homogenous conductor, such as Drake ACSR, may be found from the following equations (Fink and Beatty):

$$E_{AS} = E_{AL}\left(\frac{A_{AL}}{A_{TOTAL}}\right) + E_{ST}\left(\frac{A_{ST}}{A_{TOTAL}}\right) \tag{14.22}$$

$$\alpha_{AS} = \alpha_{AL}\left(\frac{E_{AL}}{E_{AS}}\right)\left(\frac{A_{AL}}{A_{TOTAL}}\right) + \alpha_{ST}\left(\frac{E_{ST}}{E_{AS}}\right)\left(\frac{A_{ST}}{A_{TOTAL}}\right) \tag{14.23}$$

where E_{AL} = Elastic modulus of aluminum, psi
E_{ST} = Elastic modulus of steel, psi
E_{AS} = Elastic modulus of aluminum-steel composite, psi
A_{AL} = Area of aluminum strands, square units
A_{ST} = Area of steel strands, square units
A_{TOTAL} = Total cross-sectional area, square units
α_{AL} = Aluminum coefficient of linear thermal expansion, per °F
α_{ST} = Steel coefficient of thermal elongation, per °F
α_{AS} = Composite aluminum-steel coefficient of thermal elongation, per °F

The elastic moduli for solid aluminum wire is 10 million psi and for steel wire is 30 million psi. The elastic moduli for stranded wire is reduced. The modulus for stranded aluminum is assumed to be 8.6 million psi for all strandings. The moduli for the steel core of ACSR conductors varies with stranding as follows:

- 27.5×10^6 for single-strand core
- 27.0×10^6 for 7-strand core
- 26.5×10^6 for 19-strand core

Using elastic moduli of 8.6 and 27.0 million psi for aluminum and steel, respectively, the elastic modulus for Drake ACSR is:

$$E_{AS} = (8.6 \times 10^6)\left(\frac{0.6247}{0.7264}\right) + (27.0 \times 10^6)\left(\frac{0.1017}{0.7264}\right) = 11.2 \times 10^6 \text{ psi}$$

and the coefficient of linear thermal expansion is:

$$\begin{aligned}\alpha_{AS} &= 12.8 \times 10^{-6}\left(\frac{8.6 \times 10^6}{11.2 \times 10^6}\right)\left(\frac{0.6247}{0.7264}\right) + 6.4 \times 10^{-6}\left(\frac{27.0 \times 10^6}{11.2 \times 10^6}\right)\left(\frac{0.1017}{0.7264}\right)\\ &= 10.6 \times 10^{-6}/^\circ\text{F}\end{aligned}$$

If the conductor temperature changes from a reference temperature, T_{REF}, to another temperature, T, the conductor length, L, changes in proportion to the product of the conductor's effective thermal elongation coefficient, α_{AS}, and the change in temperature, $T - T_{REF}$, as shown below:

$$L_T = L_{T_{REF}}(1 + \alpha_{AS}(T - T_{REF})) \tag{14.24}$$

For example, if the temperature of the Drake conductor in the preceding example increases from 60°F (15°C) to 167°F (75°C), then the length at 60°F increases by 0.68 ft (0.21 m) from 600.27 ft (182.96 m) to 600.95 ft (183.17 m):

$$L_{(167^\circ F)} = 600.27(1 + (10.6 \times 10^{-6})(167 - 60)) = 600.95 \text{ ft}$$

Ignoring for the moment any change in length due to change in tension, the sag at 167°F (75°C) may be calculated for the conductor length of 600.95 ft (183.17 m) using Eq. (14.8):

$$D = \sqrt{\frac{3(600)(0.95)}{8}} = 14.62 \text{ ft}$$

Using a rearrangement of Eq. (14.2), this increased sag is found to correspond to a decreased tension of:

$$H = \frac{w(S^2)}{8D} = \frac{1.094(600^2)}{8(14.62)} = 3367 \text{ lb}$$

If the conductor were inextensible, that is, if it had an infinite modulus of elasticity, then these values of sag and tension for a conductor temperature of 167°F would be correct. For any real conductor, however, the elastic modulus of the conductor is finite and changes in tension do change the conductor length. Use of the preceding calculation, therefore, will overstate the increase in sag.

14.2.2 Sag Change Due to Combined Thermal and Elastic Effects

With moduli of elasticity around the 8.6 million psi level, typical bare aluminum and ACSR conductors elongate about 0.01% for every 1000 psi change in tension. In the preceding example, the increase in temperature caused an increase in length and sag and a decrease in tension, but the effect of tension change on length was ignored.

As discussed later, concentric-lay stranded conductors, particularly non-homogenous conductors such as ACSR, are not inextensible. Rather, they exhibit quite complex elastic and plastic behavior. Initial loading of conductors results in elongation behavior substantially different from that caused by loading many years later. Also, high tension levels caused by heavy ice and wind loads cause a permanent increase in conductor length, affecting subsequent elongation under various conditions.

Accounting for such complex stress-strain behavior usually requires a sophisticated, computer-aided approach. For illustration purposes, however, the effect of permanent elongation of the conductor on sag and tension calculations will be ignored and a simplified elastic conductor assumed. This idealized conductor is assumed to elongate linearly with load and to undergo no permanent increase in length regardless of loading or temperature. For such a conductor, the relationship between tension and length is as follows:

$$L_H = L_{H_{REF}}\left(1 + \frac{H - H_{REF}}{E_C A}\right) \tag{14.25}$$

where L_H = Length of conductor under horizontal tension H

$L_{H_{REF}}$ = Length of conductor under horizontal reference tension H_{REF}

E_C = Elastic modulus of elasticity of the conductor, psi

A = Cross-sectional area, in.^{2}

In calculating sag and tension for extensible conductors, it is useful to add a step to the preceding calculation of sag and tension for elevated temperature. This added step allows a separation of thermal elongation and elastic elongation effects, and involves the calculation of a zero tension length, ZTL, at the conductor temperature of interest, T_{cdr}.

This ZTL(T_{cdr}) is the conductor length attained if the conductor is taken down from its supports and laid on the ground with no tension. By reducing the initial tension in the conductor to zero, the elastic elongation is also reduced to zero, shortening the conductor. It is possible, then, for the zero tension length to be less than the span length.

Consider the preceding example for Drake ACSR in a 600-ft level span. The initial conductor temperature is 60°F, the conductor length is 600.27 ft, and E_{AS} is calculated to be 11.2 million psi. Using Eq. (14.25), the reduction of the initial tension from 6300 lb to zero yields a ZTL (60°F) of:

$$ZTL_{(60^\circ F)} = 600.27\left(1 + \frac{0 - 6300}{(11.2 \times 10^6)0.7264}\right) = 599.81 \text{ ft}$$

Keeping the tension at zero and increasing the conductor temperature to 167°F yields a purely thermal elongation. The zero tension length at 167°F can be calculated using Eq. (14.24):

$$ZTL_{(167^\circ F)} = 599.81\left(1 + \left(10.6 \times 10^{-6}\right)\left(167 - 60\right)\right) = 600.49 \text{ ft}$$

According to Eqs. (14.2) and (14.8), this length corresponds to a sag of 10.5 ft and a horizontal tension of 4689 lb. However, this length was calculated for zero tension and will elongate elastically under tension. The actual conductor sag-tension determination requires a process of iteration as follows:

1. As described above, the conductor's zero tension length, calculated at 167°F (75°C), is 600.49 ft, sag is 10.5 ft, and the horizontal tension is 4689 lb.
2. Because the conductor is elastic, application of Eq. (14.25) shows the tension of 4689 lb will increase the conductor length from 600.49 ft to:

$$L_{l_{(167^\circ F)}} = 600.49\left(1 + \frac{4689 - 0}{0.7264(11.2 \times 10^6)}\right) = 600.84 \text{ ft}$$

3. The sag, $D_{1_{(167^\circ F)}}$, corresponding to this length is calculated using Eq. (14.8):

$$D_{l_{(167^\circ F)}} = \sqrt{\frac{3(600)(0.84)}{8}} = 13.72 \text{ ft}$$

4. Using Eq. (14.2), this sag yields a new horizontal tension, $H_{1_{(167^\circ F)}}$, of:

$$H_1 = \frac{1.094(600^2)}{8(13.7)} = 3588 \text{ lb}$$

A new trial tension is taken as the average of H and H_1, and the process is repeated. The results are described in Table 14.3.

TABLE 14.3 Interative Solution for Increased Conductor Temperature

Iteration #	Length, L_n, ft	Sag, D_n, ft	Tension, H_n, lb	New Trial Tension, lb
ZTL	600.550	11.1	4435	—
1	600.836	13.7	3593	$\frac{4435 + 3593}{2} = 4014$
2	600.809	13.5	3647	$\frac{3647 + 4014}{2} = 3831$
3	600.797	13.4	3674	$\frac{3674 + 3831}{2} = 3753$
4	600.792	13.3	3702	$\frac{3702 + 3753}{2} = 3727$

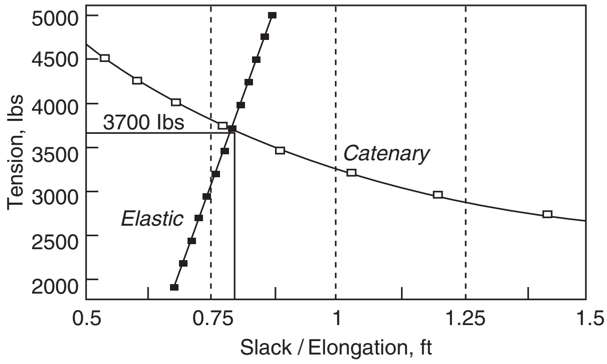


FIGURE 14.5 Sag-tension solution for 600-ft span of Drake at 167°F.

Note that the balance of thermal and elastic elongation of the conductor yields an equilibrium tension of approximately 3700 lbs and a sag of 13.3 ft. The calculations of the previous section, which ignored elastic effects, results in lower tension, 3440 lb, and a greater sag, 14.7 ft.

Slack is equal to the excess of conductor length over span length. The preceding table can be replaced by a plot of the catenary and elastic curves on a graph of slack vs tension. The solution occurs at the intersection of the two curves. Figure 14.5 shows the tension versus slack curves intersecting at a tension of 3700 lb, which agrees with the preceding calculations.

14.2.3 Sag Change Due to Ice Loading

As a final example of sag-tension calculation, calculate the sag and tension for the 600-ft Drake span with the addition of 0.5 inches of radial ice and a drop in conductor temperature to 0°F. Employing Eq. (14.17), the weight of the conductor increases by:

$$w_{ice} = 1.244t(D + t)$$

$$w_{ice} = 1.244(0.5)(1.108 + 0.5) = 1.000 \text{ lb/ft}$$

As in the previous example, the calculation uses the conductor's zero tension length at 60°F, which is the same as that found in the previous section, 599.81 ft. The ice loading is specified for a conductor temperature of 0°F, so the ZTL(0°F), using Eq. (14.24), is:

$$ZTL_{(0^\circ F)} = 599.81[1 + (10.6 \times 10^{-6})(0 - 60)] = 599.43\text{ft}$$

As in the case of sag-tension at elevated temperatures, the conductor tension is a function of slack and elastic elongation. The conductor tension and the conductor length are found at the point of intersection of the catenary and elastic curves (Fig. 14.6). The intersection of the curves occurs at a horizontal tension component of 12,275 lb, not very far from the crude initial estimate of 12,050 lb that ignored elastic effects. The sag corresponding to this tension and the iced conductor weight per unit length is 9.2 ft.

In spite of doubling the conductor weight per unit length by adding 0.5 in. of ice, the sag of the conductor is much less than the sag at 167°F. This condition is generally true for transmission conductors where minimum ground clearance is determined by the high temperature rather than the heavy loading condition. Small distribution conductors, such as the 1/0 AWG ACSR in Table 14.1, experience a much larger ice-to-conductor weight ratio (4.8), and the conductor sag under maximum wind and ice load may exceed the sag at moderately higher temperatures.

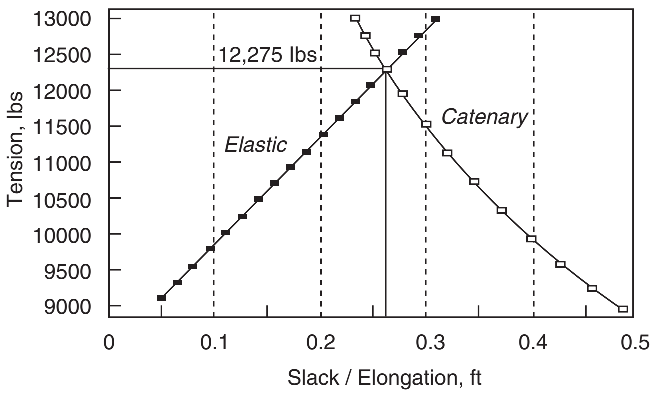


FIGURE 14.6 Sag-tension solution for 600-ft span of Drake at 0°F and 0.5 in. ice.

The preceding approximate tension calculations could have been more accurate with the use of actual stress-strain curves and graphic sag-tension solutions, as described in detail in *Graphic Method for Sag Tension Calculations for ACSR and Other Conductors* (Aluminum Company of America, 1961). This method, although accurate, is very slow and has been replaced completely by computational methods.

14.3 Numerical Sag-Tension Calculations

Sag-tension calculations are normally done numerically and allow the user to enter many different loading and conductor temperature conditions. Both initial and final conditions are calculated and multiple tension constraints can be specified. The complex stress-strain behavior of ACSR-type conductors can be modeled numerically, including both temperature, and elastic and plastic effects.

14.3.1 Stress-Strain Curves

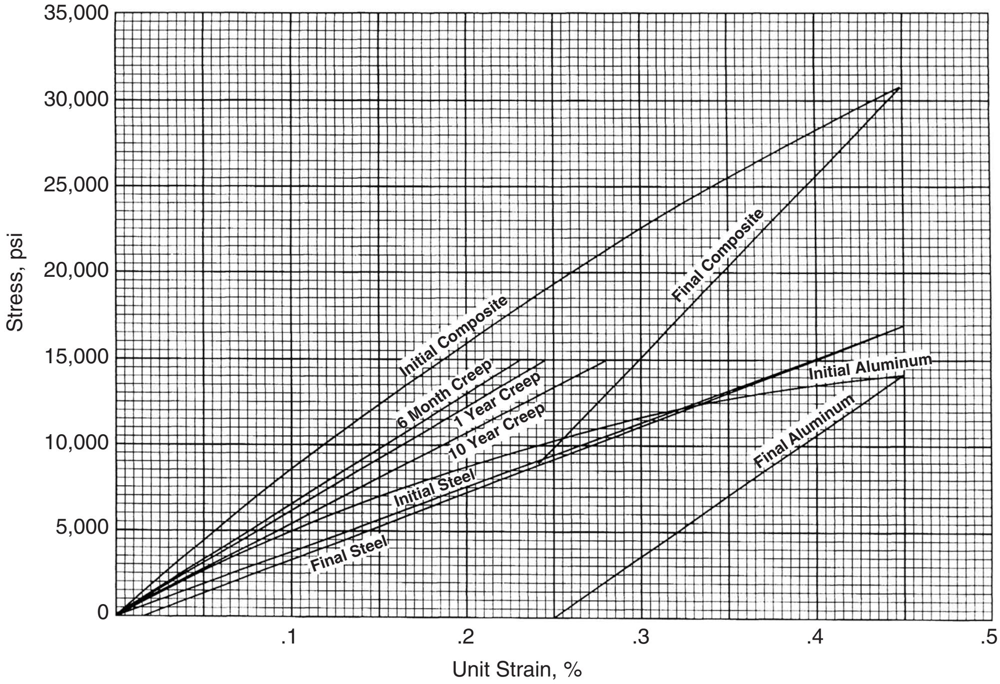
Stress-strain curves for bare overhead conductor include a minimum of an initial curve and a final curve over a range of elongations from 0 to 0.45%. For conductors consisting of two materials, an initial and final curve for each is included. Creep curves for various lengths of time are typically included as well.

Overhead conductors are not purely elastic. They stretch with tension, but when the tension is reduced to zero, they do not return to their initial length. That is, conductors are plastic; the change in conductor length cannot be expressed with a simple linear equation, as for the preceding hand calculations. The permanent length increase that occurs in overhead conductors yields the difference in initial and final sag-tension data found in most computer programs.

Figure 14.7 shows a typical stress-strain curve for a 26/7 ACSR conductor (Aluminum Association, 1974); the curve is valid for conductor sizes ranging from 266.8 to 795 kcmil. A 795 kcmil-26/7 ACSR "Drake" conductor has a breaking strength of 31,500 lb (14,000 kg) and an area of 0.7264 in.^{2} (46.9 mm^2) so that it fails at an average stress of 43,000 psi (30 kg/mm^2). The stress-strain curve illustrates that when the percent of elongation at a stress is equal to 50% of the conductor's breaking strength (21,500 psi), the elongation is less than 0.3% or 1.8 ft (0.55 m) in a 600-ft (180 m) span.

Note that the component curves for the steel core and the aluminum stranded outer layers are separated. This separation allows for changes in the relative curve locations as the temperature of the conductor changes.

For the preceding example, with the Drake conductor at a tension of 6300 lb (2860 kg), the length of the conductor in the 600-ft (180 m) span was found to be 0.27 ft longer than the span. This tension corresponds to a stress of 8600 psi (6.05 kg/mm^2). From the stress-strain curve in Fig. 14.7, this corresponds to an initial elongation of 0.105% (0.63 ft). As in the preceding hand calculation, if the conductor is reduced to zero tension, its unstressed length would be less than the span length.



Equations for Curves (X = unit strain in %; Y = stress in psi) :

Initial composite: $X = 4.07 \times 10^{-3} + (1.28 \times 10^{-5})\,Y - (1.18 \times 10^{-10})\,Y^2 + (5.64 \times 10^{-15})\,Y^3$

$Y = -512 + (8.617 \times 10^4)\,X - (1.18 \times 10^4)\,X^2 - (5.76 \times 10^{-4})\,X^3$

Initial Steel: $Y = (37.15 \times 10^3)\,X$

Initial Aluminum: $Y = -512 = (4.902 \times 10^4)\,X - (1.18 \times 10^4)\,X^2 - (5.76 \times 10^4)\,X^3$

Final Composite: $Y = (107.55\,X - 17.65) \times 10^3$

Final Steel: $Y = (38.60\,X - 0.65) \times 10^3$

Final Aluminum: $Y = (68.95\,X - 17.00) \times 10^3$

6 Month Creep: $Y = (68.75 \times 10^3)\,X$

1 Year Creep: $Y = (60.60 \times 10^3)\,X$

10 Year Creep: $Y = (53.45 \times 10^3)\,X$

Test Temperature 70°F to 75°F

FIGURE 14.7 Stress-strain curves for 26/7 ACSR.

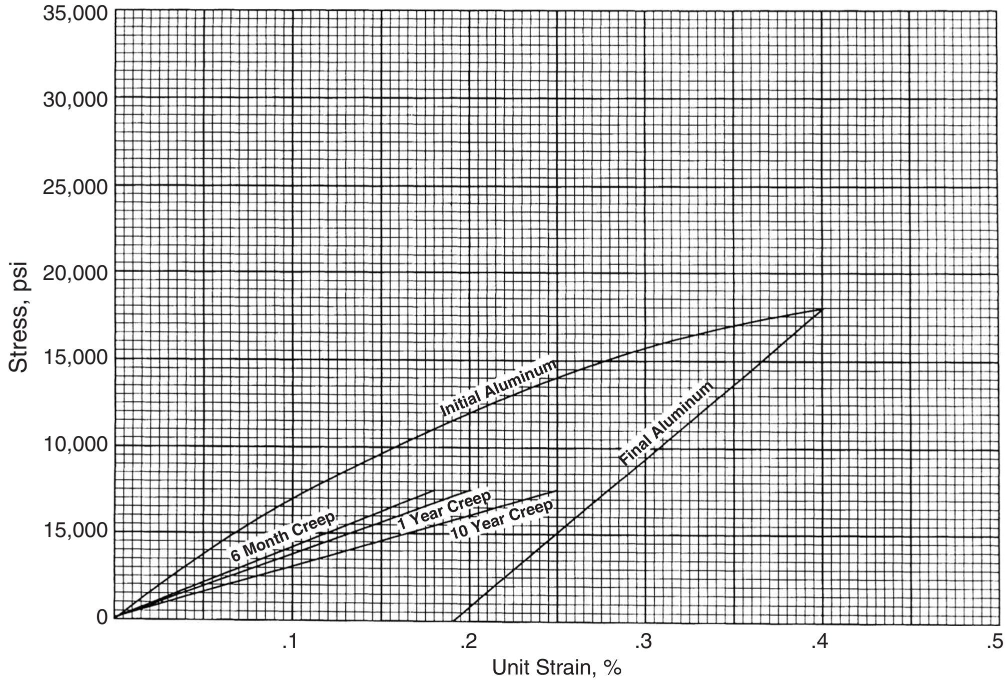
Figure 14.8 is a stress-strain curve (Aluminum Association, 1974) for an all-aluminum 37-strand conductor ranging in size from 250 kcmil to 1033.5 kcmil. Because the conductor is made entirely of aluminum, there is only one initial and final curve.

14.3.1.1 Permanent Elongation

Once a conductor has been installed at an initial tension, it can elongate further. Such elongation results from two phenomena: permanent elongation due to high tension levels resulting from ice and wind loads, and creep elongation under everyday tension levels. These types of conductor elongation are discussed in the following sections.

14.3.1.2 Permanent Elongation Due to Heavy Loading

Both Figs. 14.7 and 14.8 indicate that when the conductor is initially installed, it elongates following the initial curve that is not a straight line. If the conductor tension increases to a relatively high level under ice and wind loading, the conductor will elongate. When the wind and ice loads abate, the conductor



Equations for Curves (X = unit strain in %; Y = stress in psi):

Initial Aluminum: $X = -5.31 \times 10^{-3} + (1.74 \times 10^{-5})\,Y - (6.17 \times 10^{-10})\,Y^2 + (5.05 \times 10^{-14})\,Y^3$

$Y = 136 + (7.46 \times 10^4)\,X - (8.51 \times 10^4)\,X^2 + (2.33 \times 10^4)\,X^3$

Final Aluminum: $Y = (85.20\,X - 16.14) \times 10^3$

6 Month Creep: $Y = (42.30 \times 10^3)\,X$

1 Year Creep: $Y = (38.20 \times 10^3)\,X$

10 Year Creep: $Y = (30.60 \times 10^3)\,X$

Test Temperature 70°F to 75°F

FIGURE 14.8 Stress-strain curves for 37-strand AAC.

elongation will reduce along a curve parallel to the final curve, but the conductor will never return to its original length.

For example, refer to Fig. 14.8 and assume that a newly strung 795 kcmil-37 strand AAC "Arbutus" conductor has an everyday tension of 2780 lb. The conductor area is 0.6245 in.^{2}, so the everyday stress is 4450 psi and the elongation is 0.062%. Following an extremely heavy ice and wind load event, assume that the conductor stress reaches 18,000 psi. When the conductor tension decreases back to everyday levels, the conductor elongation will be permanently increased by more than 0.2%. Also the sag under everyday conditions will be correspondingly higher, and the tension will be less. In most numerical sag-tension methods, final sag-tensions are calculated for such permanent elongation due to heavy loading conditions.

14.3.1.3 Permanent Elongation at Everyday Tensions (Creep Elongation)

Conductors permanently elongate under tension even if the tension level never exceeds everyday levels. This permanent elongation caused by everyday tension levels is called creep (Aluminum Company of America, 1961). Creep can be determined by long-term laboratory creep tests, the results of which are used to generate creep curves. On stress-strain graphs, creep curves are usually shown for 6-mo, 1-yr, and 10-yr periods. Figure 14.8 shows these typical creep curves for a 37 strand 250.0 through 1033.5 kcmil AAC. In Fig. 14.8 assume that the conductor tension remains constant at the initial stress of 4450 psi. At the intersection of this stress level and the initial elongation curve, 6-month, 1-year, and 10-year creep curves, the conductor elongation from the initial elongation of 0.062% increases to 0.11%, 0.12%, and 0.15%, respectively. Because of creep elongation, the resulting final sags are greater and the conductor tension is less than the initial values.

Creep elongation in aluminum conductors is quite predictable as a function of time and obeys a simple exponential relationship. Thus, the permanent elongation due to creep at everyday tension can be found for any period of time after initial installation. Creep elongation of copper and steel conductors is much less and is normally ignored.

Permanent increase in conductor length due to heavy load occurrences cannot be predicted at the time that a line is built. The reason for this unpredictability is that the occurrence of heavy ice and wind is random. A heavy ice storm may occur the day after the line is built or may never occur over the life of the line.

14.3.2 Sag-Tension Tables

To illustrate the result of typical sag-tension calculations, refer to Tables 14.4 through 14.9 showing initial and final sag-tension data for 795 kcmil-26/7 ACSR "Drake", 795 kcmil-37 strand AAC "Arbutus", and 795-kcmil Type 16 "Drake/SDC" conductors in NESC light and heavy loading areas for spans of

TABLE 14.4 Sag and Tension Data for 795 kcmil-26/7 ACSR "Drake" Conductor

Span = 600 ft
NESC Heavy
Loading District

Creep is ***not*** a factor

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Resultant Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.509	11.14	10153 5415 Al 4738 St	11.14	10153 5415 Al 4738 St
32	0.50	0.00	0.00	2.094	44.54	8185 3819 Al 4366 St	11.09	8512 4343 Al 4169 St
−20	0.00	0.00	0.00	1.094	6.68	7372 3871 Al 3501 St	6.27	7855 4465 Al 3390 St
0	0.00	0.00	0.00	1.094	7.56	6517 3111 Al 3406 St	6.89	7147 3942 Al 3205 St
30	0.00	0.00	0.00	1.094	8.98	5490 2133 Al 3357 St	7.95	6197 3201 Al 2996 St
60	0.00	0.00	0.00	1.094	10.44	4725[a] 1321 Al 3404 St	9.12	5402 2526 Al 2875 St
90	0.00	0.00	0.00	1.094	11.87	4157 634 Al 3522 St	10.36	4759 1922 Al 2837 St
120	0.00	0.00	0.00	1.094	13.24	3727 35 Al 3692 St	11.61	4248 1379 Al 2869 St
167	0.00	0.00	0.00	1.094	14.29	3456 0 Al 3456 St	13.53	3649 626 Al 3022 St
212	0.00	0.00	0.00	1.094	15.24	3241 0 Al 3241 St	15.24	3241 0 Al 3239 St

[a]Design condition.

TABLE 14.5 Tension Differences in Adjacent Dead-End Spans

Conductor: Drake
795 kcmil-26/7 ACSR — **Span = 700 ft**
Area = 0.7264 in.^{2}
Creep ***is*** a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Resultant Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.509	13.61	11318	13.55	11361
32	0.50	0.00	0.00	2.094	13.93	9224	13.33	9643
−20	0.00	0.00	0.00	1.094	8.22	8161	7.60	8824
0	0.00	0.00	0.00	1.094	9.19	7301	8.26	8115
30	0.00	0.00	0.00	1.094	10.75	6242	9.39	7142
60	0.00	0.00	0.00	1.094	12.36	5429	10.65	6300[a]
90	0.00	0.00	0.00	1.094	13.96	4809	11.99	5596
120	0.00	0.00	0.00	1.094	15.52	4330	13.37	5020
167	0.00	0.00	0.00	1.094	16.97	3960	15.53	4326
212	0.00	0.00	0.00	1.094	18.04	3728	17.52	3837

[a]Design condition.

Conductor: Drake
795 kcmil-26/7 ACSR — **Span = 1000 ft**
Area = 0.7264 in.^{2}
Creep is ***not*** a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Resultant Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.509	25.98	12116	25.98	12116
32	0.50	0.00	0.00	2.094	26.30	9990	25.53	10290
−20	0.00	0.00	0.00	1.094	18.72	7318	17.25	7940
0	0.00	0.00	0.00	1.094	20.09	6821	18.34	7469
30	0.00	0.00	0.00	1.094	22.13	6197	20.04	6840
60	0.00	0.00	0.00	1.094	24.11	5689	21.76	6300[a]
90	0.00	0.00	0.00	1.094	26.04	5271	23.49	5839
120	0.00	0.00	0.00	1.094	27.89	4923	25.20	5444
167	0.00	0.00	0.00	1.094	30.14	4559	27.82	4935
212	0.00	0.00	0.00	1.094	31.47	4369	30.24	4544

[a]Design condition.

1000 and 300 ft. Typical tension constraints of 15% final unloaded at 60°F, 25% initial unloaded at 60°F, and 60% initial at maximum loading are used.

With most sag-tension calculation methods, final sags are calculated for both heavy ice/wind load and for creep elongation. The final sag-tension values reported to the user are those with the greatest increase in sag.

14.3.2.1 Initial vs. Final Sags and Tensions

Rather than calculate the line sag as a function of time, most sag-tension calculations are determined based on initial and final loading conditions. Initial sags and tensions are simply the sags and tensions at the time the line is built. Final sags and tensions are calculated if (1) the specified ice and wind loading has occurred, and (2) the conductor has experienced 10 years of creep elongation at a conductor temperature of 60°F at the user-specified initial tension.

TABLE 14.6 Sag and Tension Data for 795 kcmil-26/7 ACSR "Drake" 600-ft Ruling Span

Conductor: Drake
795 kcmil-26/7 ACSR — **Span = 600 ft**
Area = 0.7264 in.^{2}
Creep is ***not*** a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Resultant Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.509	11.14	10153	11.14	10153
32	0.50	0.00	0.00	2.094	11.54	8185	11.09	8512
−20	0.00	0.00	0.00	1.094	6.68	7372	6.27	7855
0	0.00	0.00	0.00	1.094	7.56	6517	6.89	7147
30	0.00	0.00	0.00	1.094	8.98	5490	7.95	6197
60	0.00	0.00	0.00	1.094	10.44	4725[a]	9.12	5402
90	0.00	0.00	0.00	1.094	11.87	4157	10.36	4759
120	0.00	0.00	0.00	1.094	13.24	3727	11.61	4248
167	0.00	0.00	0.00	1.094	14.29	3456	13.53	3649
212	0.00	0.00	0.00	1.094	15.24	3241	15.24	3241

[a]Design condition.

TABLE 14.7 Stringing Sag Table for 795 kcmil-26/7 ACSR "Drake" 600-ft Ruling Span

600-ft Ruling Span

Controlling Design Condition:
15% RBS at 60°F, No Ice or Wind, Final

NESC Heavy Load District

Horizontal Tension, lb	6493	6193	5910	5645	5397	5166	4952	4753	4569
Temp, °F	20	30	40	50	60	70	80	90	100
Spans	Sag, ft-in.	Sag, ft-in.	Sag, ft-in.	Sag, ft-in.	Sag, ft-in.	Sag, ft-in.	Sag, ft-in.	Sag, ft-in.	Sag, ft-in.
400	3 - 4	3 - 6	3 - 8	3 - 11	4 - 1	4 - 3	4 - 5	4 - 7	4 - 9
410	3 - 6	3 - 9	3 - 11	4 - 1	4 - 3	4 - 5	4 - 8	4 - 10	5 - 0
420	3 - 9	3 - 11	4 - 1	4 - 3	4 - 6	4 - 8	4 - 10	5 - 1	5 - 3
430	3 - 11	4 - 1	4 - 3	4 - 6	4 - 8	4 - 11	5 - 1	5 - 4	5 - 6
440	4 - 1	4 - 3	4 - 6	4 - 8	4 - 11	5 - 2	5 - 4	5 - 7	5 - 10
450	4 - 3	4 - 6	4 - 8	4 - 11	5 - 2	5 - 4	5 - 7	5 - 10	6 - 1
460	4 - 5	4 - 8	4 - 11	5 - 2	5 - 4	5 - 7	5 - 10	6 - 1	6 - 4
470	4 - 8	4 - 11	5 - 1	5 - 4	5 - 7	5 - 10	6 - 1	6 - 4	6 - 7
480	4 - 10	5 - 1	5 - 4	5 - 7	5 - 10	6 - 1	6 - 4	6 - 8	6 - 11
490	5 - 1	5 - 4	5 - 7	5 - 10	6 - 1	6 - 4	6 - 8	6 - 11	7 - 2
500	5 - 3	5 - 6	5 - 9	6 - 1	6 - 4	6 - 7	6 - 11	7 - 2	7 - 6
510	5 - 6	5 - 9	6 - 0	6 - 4	6 - 7	6 - 11	7 - 2	7 - 6	7 - 9
520	5 - 8	6 - 0	6 - 3	6 - 7	6 - 10	7 - 2	7 - 6	7 - 9	8 - 1
530	5 - 11	6 - 2	6 - 6	6 - 10	7 - 1	7 - 5	7 - 9	8 - 1	8 - 5
540	6 - 2	6 - 5	6 - 9	7 - 1	7 - 5	7 - 9	8 - 1	8 - 5	8 - 9
550	6 - 4	6 - 8	7 - 0	7 - 4	7 - 8	8 - 0	8 - 4	8 - 8	9 - 1
560	6 - 7	6 - 11	7 - 3	7 - 7	7 - 11	8 - 4	8 - 8	9 - 0	9 - 5
570	6 - 10	7 - 2	7 - 6	7 - 10	8 - 3	8 - 7	9 - 0	9 - 4	9 - 9
580	7 - 1	7 - 5	7 - 9	8 - 2	8 - 6	8 - 11	9 - 4	9 - 8	10 - 1
590	7 - 4	7 - 8	8 - 1	8 - 5	8 - 10	9 - 3	9 - 7	10 - 0	10 - 5
600	7 - 7	7 - 11	8 - 4	8 - 9	9 - 1	9 - 6	9 - 11	10 - 4	10 - 9
610	7 - 1	8 - 3	8 - 7	9 - 0	9 - 5	9 - 10	10 - 3	10 - 9	11 - 2
620	8 - 1	8 - 6	8 - 11	9 - 4	9 - 9	10 - 2	10 - 7	11 - 1	11 - 6
630	8 -	8 - 9	9 - 2	9 - 7	10 - 1	10 - 6	11 - 0	11 - 5	11 - 11
640	8 - 8	9 - 1	9 - 6	9 - 11	10 - 5	10 - 10	11 - 4	11 - 9	12 - 3
650	8 - 11	9 - 4	9 - 9	10 - 3	10 - 9	11 - 2	11 - 8	12 - 2	12 - 8
660	9 - 2	9 - 7	10 - 1	10 - 7	11 - 1	11 - 6	12 - 0	12 - 6	13 - 1
670	9 - 5	9 - 11	10 - 5	10 - 11	11 - 5	11 - 11	12 - 5	12 - 11	13 - 5
680	9 - 9	10 - 3	10 - 8	11 - 2	11 - 9	12 - 3	12 - 9	13 - 4	13 - 10
690	10 - 0	10 - 6	11 - 0	11 - 6	12 - 1	12 - 7	13 - 2	13 - 8	14 - 3
700	10 - 4	10 - 10	11 - 4	11 - 11	12 - 5	13 - 0	13 - 6	14 - 1	14 - 8

TABLE 14.8 Time-Sag Table for Stopwatch Method

Return of Wave											
Sag, in.	3rd Time, sec	5th Time, sec	Sag, in.	3rd Time, sec	5th Time, sec	Sag, in.	3rd Time, sec	5th Time, sec	Sag, in.	3rd Time, sec	5th Time, sec
5	1.9	3.2	55	6.4	10.7	105	8.8	14.7	155	10.7	17.9
6	2.1	3.5	56	6.5	10.8	106	8.9	14.8	156	10.8	18.0
7	2.3	3.8	57	6.5	10.9	107	8.9	14.9	157	10.8	18.0
8	2.4	4.1	58	6.6	11.1	109	9.0	15.0	158	10.9	18.1
9	2.6	4.3	59	6.6	11.1	109	9.0	15.0	159	10.9	18.1
10	2.7	4.6	60	6.7	11.1	110	9.1	15.1	160	10.9	18.2
11	2.9	4.8	61	6.7	11.2	111	9.1	15.2	161	11.0	18.2
12	3.0	5.0	62	6.8	11.3	112	9.1	15.2	162	11.0	18.2
13	3.1	5.2	63	6.9	11.4	113	9.2	15.3	163	11.0	18.4
14	3.2	5.4	64	6.9	11.5	114	9.2	15.4	164	11.1	18.4
15	3.3	5.6	65	7.0	11.6	115	9.3	15.4	165	11.1	18.5
16	3.5	5.8	66	7.0	11.7	116	9.3	15.5	166	11.1	18.5
17	3.6	5.9	67	7.1	11.8	117	9.3	15.6	167	11.2	18.6
18	3.7	6.1	68	7.1	11.9	118	9.4	15.6	168	11.2	18.7
19	3.8	6.3	69	7.2	12.0	119	9.4	15.7	169	11.2	18.7
20	3.9	6.4	70	7.2	12.0	120	9.5	15.8	170	11.3	18.8
21	4.0	6.6	71	7.3	12.1	121	9.5	15.8	171	11.3	18.8
22	4.0	6.7	72	7.3	12.2	122	9.5	15.9	172	11.3	18.9
23	4.1	6.9	73	7.4	12.3	123	9.6	16.0	173	11.4	18.9
24	4.2	7.0	74	7.4	12.4	124	9.6	16.0	174	11.4	19.0
25	4.3	7.2	75	7.5	12.5	125	9.7	16.1	175	11.4	19.0
26	4.4	7.3	76	7.5	12.5	126	9.7	16.2	176	11.4	19.1
27	4.5	7.5	77	7.6	12.6	127	9.7	16.2	177	11.5	19.1
28	4.6	7.6	78	7.6	12.7	128	9.8	16.3	178	11.5	19.2
29	4.6	7.7	79	7.7	12.8	129	9.8	16.3	179	11.5	19.3
30	4.7	7.9	80	7.7	12.9	130	9.8	16.4	180	11.6	19.3
31	4.8	8.0	81	7.8	13.0	131	9.9	16.5	181	11.6	19.4
32	4.9	8.1	82	7.8	13.0	132	9.9	16.5	182	11.6	19.4
33	5.0	8.3	83	7.9	13.1	133	10.0	16.6	183	11.7	19.5
34	5.0	8.4	84	7.9	13.2	134	10.0	16.7	184	11.7	19.5
35	5.1	8.5	85	8.0	13.3	135	10.0	16.7	185	11.7	19.6
36	5.2	8.6	86	8.0	13.3	136	10.1	16.8	186	11.8	19.6
37	5.3	8.8	87	8.1	13.4	137	10.1	16.8	187	11.8	19.7
38	5.3	8.9	88	8.1	13.5	138	10.1	16.9	188	11.8	19.7
39	5.4	9.0	89	8.1	13.6	139	10.2	17.0	189	11.9	19.8
40	5.5	9.1	90	8.2	13.7	140	10.2	17.0	190	11.9	19.8
41	5.5	9.2	91	8.2	13.7	141	10.3	17.1	191	11.9	19.9
42	5.6	9.3	92	8.3	13.8	142	10.3	17.1	192	12.0	19.9
43	5.7	9.4	93	8.3	13.9	143	10.3	17.2	193	12.0	20.0
44	5.7	9.5	94	8.4	14.0	144	10.4	17.3	194	12.0	20.0
45	5.8	9.7	95	8.4	14.0	145	10.4	17.3	195	12.1	20.1
46	5.9	9.8	96	8.5	14.1	146	10.4	17.4	196	12.1	20.1
47	5.9	9.9	97	8.5	14.2	147	10.5	17.4	197	12.1	20.2
48	6.0	10.0	98	8.5	14.2	148	10.5	17.5	198	12.1	20.0
49	6.0	10.1	99	8.6	14.3	149	10.5	17.6	199	12.2	20.3
50	6.1	10.2	100	8.6	14.4	150	10.6	17.6	200	12.2	20.3
51	6.2	10.3	101	8.7	14.5	151	10.6	17.7	201	12.2	20.4
52	6.2	10.4	102	8.7	14.5	152	10.6	17.7	202	12.3	20.5
53	6.3	10.5	103	8.8	14.6	153	10.7	17.8	203	12.3	20.5
54	6.3	10.6	104	8.8	14.7	154	10.7	17.9	204	12.3	20.6

Note: To calculate the time of return of other waves, multiply the time in seconds for one wave return by the number of wave returns or, more simply, select the combination of values from the table that represents the number of wave returns desired. For example, the time of return of the 8th wave is the sum of the 3rd and 5th, while for the 10th wave it is twice the time of the 5^{th}.

The approximate formula giving the relationship between sag and time is given as:

$$D = 12.075\left(\frac{T}{N}\right)^2 \ (inches)$$

where $D =$ sag, in.

$T =$ time, sec

$N =$ number of return waves counted

TABLE 14.9 Typical Sag and Tension Data 795 kcmil-26/7 ACSR "Drake," 300- and 1000-ft Spans

Conductor: Drake
795 kcmil-26/7 ACSR
Area = 0.7264 in.^{2}
Creep *is* a factor

Span = 300 ft

NESC Heavy Loading District

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
30	0.00	9.00	0.05	1.424	2.37	6769	2.09	7664
30	0.00	0.00	0.00	1.094	1.93	6364	1.66	7404
60	0.00	0.00	0.00	1.094	2.61	4725[a]	2.04	6033
90	0.00	0.00	0.00	1.094	3.46	3556	2.57	4792
120	0.00	0.00	0.00	1.094	1.00	3077	3.25	3785
167	0.00	0.00	0.00	1.094	4.60	2678	4.49	2746
212	0.00	0.00	0.00	1.094	5.20	2371	5.20	2371

[a]Design condition.

Conductor: Drake
795 kcmil-26/7 ACSR
Area = 0.7264 in.^{2}
Creep *is* a factor

Span = 1000 ft

NESC Heavy Loading District

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
30	0.00	9.00	0.05	1.424	28.42	6290	27.25	6558
30	0.00	0.00	0.00	1.094	27.26	5036	25.70	5339
60	0.00	0.00	0.00	1.094	29.07	4725[a]	27.36	5018
90	0.00	0.00	0.00	1.094	30.82	4460	28.98	4740
120	0.00	0.00	0.00	1.094	32.50	4232	30.56	4498
167	0.00	0.00	0.00	1.094	34.49	3990	32.56	4175
212	0.00	0.00	0.00	1.094	35.75	3851	35.14	3917

[a]Design condition.

Note: **Calculations based on:** (1) NESC Light Loading District. (2) Tension Limits: a. Initial Loaded – 60% RBS @ 30°F; b. Initial Unloaded – 25% RBS @ 60°F; c. Final Unloaded – 15% RBS @ 60°F.

14.3.2.2 Special Aspects of ACSR Sag-Tension Calculations

Sag-tension calculations with ACSR conductors are more complex than such calculations with AAC, AAAC, or ACAR conductors. The complexity results from the different behavior of steel and aluminum strands in response to tension and temperature. Steel wires do not exhibit creep elongation or plastic elongation in response to high tensions. Aluminum wires do creep and respond plastically to high stress levels. Also, they elongate twice as much as steel wires do in response to changes in temperature.

Table 14.10 presents various initial and final sag-tension values for a 600-ft span of a Drake ACSR conductor under heavy loading conditions. Note that the tension in the aluminum and steel components is shown separately. In particular, some other useful observations are:

1. At 60°F, without ice or wind, the tension level in the aluminum strands decreases with time as the strands permanently elongate due to creep or heavy loading.
2. Both initially and finally, the tension level in the aluminum strands decreases with increasing temperature reaching zero tension at 212°F and 167°F for initial and final conditions, respectively.
3. At the highest temperature (212°F), where all the tension is in the steel core, the initial and final sag-tensions are nearly the same, illustrating that the steel core does not permanently elongate in response to time or high tension.

TABLE 14.10 Typical Sag and Tension Data 795 kcmil-26/7 ACSR "Drake," 300- and 1000-ft Spans

Conductor: Drake
795 kcmil-26/7 ACSR/SD
Area = 0.7264 in.^{2}
Creep ***is*** a factor

Span = 300 ft

NESC Heavy Loading District

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.509	2.91	9695	2.88	9802
32	0.50	0.00	0.00	2.094	3.13	7528	2.88	8188
−20	0.00	0.00	0.00	1.094	1.26	9733	1.26	9756
0	0.00	0.00	0.00	1.094	1.48	8327	1.40	8818
30	0.00	0.00	0.00	1.094	1.93	6364	1.66	7404
60	0.00	0.00	0.00	1.094	2.61	4725[a]	2.04	6033
90	0.00	0.00	0.00	1.094	3.46	3556	2.57	4792
120	0.00	0.00	0.00	1.094	4.00	3077	3.25	3785
167	0.00	0.00	0.00	1.094	4.60	2678	4.49	2746
212	0.00	0.00	0.00	1.094	5.20	2371	5.20	2371

[a] Design condition.

Conductor: Drake
795 kcmil-26/7 ACSR
Area = 0.7264 in.^{2}
Creep is ***not*** a factor

Span = 1000 ft

NESC Heavy Loading District

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.509	30.07	10479	30.07	10479
32	0.50	0.00	0.00	2.094	30.56	8607	29.94	8785
−20	0.00	0.00	0.00	1.094	24.09	5694	22.77	6023
0	0.00	0.00	0.00	1.094	25.38	5406	23.90	5738
30	0.00	0.00	0.00	1.094	27.26	5036	25.59	5362
60	0.00	0.00	0.00	1.094	29.07	4725[a]	27.25	5038
90	0.00	0.00	0.00	1.094	30.82	4460	28.87	4758
120	0.00	0.00	0.00	1.094	32.50	4232	30.45	4513
167	0.00	0.00	0.00	1.094	34.36	4005	32.85	4187
212	0.00	0.00	0.00	1.094	35.62	3865	35.05	3928

[a] Design condition.

Note: **Calculations based on:** (1) NESC Heavy Loading District. (2) Tension Limits: a. Initial Loaded – 60% RBS @ 0°F; b. Initial Unloaded – 25% RBS @ 60°F; c. Final Unloaded – 15% RBS @ 60°F.

14.4 Ruling Span Concept

Transmission lines are normally designed in line sections with each end of the line section terminated by a strain structure that allows no longitudinal (along the line) movement of the conductor (Winkelman, 1959). Structures within each line section are typically suspension structures that support the conductor vertically, but allow free movement of the conductor attachment point either longitudinally or transversely.

14.4.1 Tension Differences for Adjacent Dead-End Spans

Table 14.11 contains initial and final sag-tension data for a 700-ft and a 1000-ft dead-end span when a Drake ACSR conductor is initially installed to the same 6300-lb tension limits at 60°F. Note that the

TABLE 14.11 Typical Sag and Tension Data 795 kcmil-Type 16 ACSR/SD, 300- and 1000-ft Spans

Conductor: Drake
795 kcmil-Type 16 ACSR/SD — **Span = 300 ft**
Area = 0.7261 in.^{2}
Creep *is* a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
30	0.00	9.00	0.05	1.409	1.59	9980	1.31	12373
30	0.00	0.00	0.00	1.093	1.26	9776	1.03	11976
60	0.00	0.00	0.00	1.093	1.60	7688	1.16	10589[a]
90	0.00	0.00	0.00	1.093	2.12	5806	1.34	9159
120	0.00	0.00	0.00	1.093	2.69	4572	1.59	7713
167	0.00	0.00	0.00	1.093	3.11	3957	2.22	5545
212	0.00	0.00	0.00	1.093	3.58	3435	3.17	3877

[a]Design condition.

Conductor: Drake
795 kcmil-Type 16 ACSR/SD — **Span = 1000 ft**
Area = 0.7261 in.^{2}
Creep *is* a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
30	0.00	9.00	0.05	1.409	17.21	10250	15.10	11676
30	0.00	0.00	0.00	1.093	15.22	8988	12.69	10779
60	0.00	0.00	0.00	1.093	17.21	7950[a]	13.98	9780
90	0.00	0.00	0.00	1.093	19.26	7108	15.44	8861
120	0.00	0.00	0.00	1.093	21.31	6428	17.03	8037
167	0.00	0.00	0.00	1.093	24.27	5647	19.69	6954
212	0.00	0.00	0.00	1.093	25.62	5352	22.32	6136

[a]Design condition.

Note: **Calculations based on:** (1) NESC Light Loading District. (2) Tension Limits: a. Initial Loaded – 60% RBS @ 30°F; b. Initial Unloaded – 25% RBS @ 60°F; c. Final Unloaded – 15% RBS @ 60°F.

difference between the initial and final limits at 60°F is approximately 460 lb. Even the initial tension (equal at 60°F) differs by almost 900 lb at −20°F and 600 lb at 167°F.

14.4.2 Tension Equalization by Suspension Insulators

At a typical suspension structure, the conductor is supported vertically by a suspension insulator assembly, but allowed to move freely in the direction of the conductor axis. This conductor movement is possible due to insulator swing along the conductor axis. Changes in conductor tension between spans, caused by changes in temperature, load, and time, are normally equalized by insulator swing, eliminating horizontal tension differences across suspension structures.

14.4.3 Ruling Span Calculation

Sag-tension can be found for a series of suspension spans in a line section by use of the ruling span concept (Ehrenberg, 1935; Winkelman, 1959). The ruling span (RS) for the line section is defined by the following equation:

$$RS = \sqrt{\frac{S_1{}^3 + S_2{}^3 + \cdots + S_n{}^3}{S_1 + S_2 + \cdots + S_n}} \tag{14.26}$$

where RS = Ruling span for the line section containing n suspension spans

S_1 = Span length of first suspension span

S_2 = Span length of second suspension span

S_n = Span length of nth suspension span

Alternatively, a generally satisfactory method for estimating the ruling span is to take the sum of the average suspension span length plus two-thirds of the difference between the maximum span and the average span. However, some judgment must be exercised in using this method because a large difference between the average and maximum span may cause a substantial error in the ruling span value.

As discussed, suspension spans are supported by suspension insulators that are free to move in the direction of the conductor axis. This freedom of movement allows the tension in each suspension span to be assumed to be the same and equal to that calculated for the ruling span. This assumption is valid for the suspension spans and ruling span under the same conditions of temperature and load, for both initial and final sags. For level spans, sag in each suspension span is given by the parabolic sag equation:

$$D_i = \frac{w(S_i^{\,2})}{8H_{RS}} \tag{14.27}$$

where D_i = sag in the ith span

S_i = span length of the ith span

H_{RS} = tension from ruling span sag-tension calculations

The sag in level suspension spans may also be calculated using the ratio:

where D_{RS} = sag in ruling span

Suspension spans vary in length, though typically not over a large range. Conductor temperature during sagging varies over a range considerably smaller than that used for line design purposes.

If the sag in any suspension span exceeds approximately 5% of the span length, a correction factor should be added to the sags obtained from the above equation or the sag should be calculated using catenary Eq. (14.29). This correction factor may be calculated as follows:

$$Correction = D^2\frac{w}{6H} \tag{14.28}$$

where D = sag obtained from parabolic equation

w = weight of conductor, lb/ft

H = horizontal tension, lb

The catenary equation for calculating the sag in a suspension or stringing span is:

$$Sag = \frac{H}{w}\left(\cosh\frac{Sw}{2H} - 1\right) \tag{14.29}$$

where S = span length, ft

H = horizontal tension, lb

w = resultant weight, lb/ft

14.4.4 Stringing Sag Tables

Conductors are typically installed in line section lengths consisting of multiple spans. The conductor is pulled from the conductor reel at a point near one strain structure progressing through travelers attached to each suspension structure to a point near the next strain structure. After stringing, the

TABLE 14.12 Typical Sag and Tension Data 795 kcmil-Type 16 ACSR/SD, 300- and 1000-ft Span

Conductor: Drake
795 kcmil-Type 16 ACSR/SD — **Span = 300 ft**
Area = 0.7261 in.^{2}
Creep ***is*** a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.486	2.19	12774	2.03	13757
32	0.50	0.00	0.00	2.074	2.25	10377	1.90	12256
−20	0.00	0.00	0.00	1.093	.91	13477	.87	14156
0	0.00	0.00	0.00	1.093	1.03	11962	.92	13305
30	0.00	0.00	0.00	1.093	1.26	9776	1.03	11976
60	0.00	0.00	0.00	1.093	1.60	7688	1.16	10589[a]
90	0.00	0.00	0.00	1.093	2.12	5806	1.34	9159
120	0.00	0.00	0.00	1.093	2.69	4572	1.59	7713
167	0.00	0.00	0.00	1.093	3.11	3957	2.22	5545
212	0.00	0.00	0.00	1.093	3.58	3435	3.17	3877

[a]Design Condition

Conductor: Drake
795 kcmil-Type 16 ACSR/SD — **Span = 1000 ft**
Area = 0.7261 in.^{2}
Creep ***is*** a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.486	20.65	15089	20.36	15299
32	0.50	0.00	0.00	2.074	20.61	12607	19.32	13445
−20	0.00	0.00	0.00	1.093	12.20	11205	10.89	12552
0	0.00	0.00	0.00	1.093	13.35	10244	11.56	11832
30	0.00	0.00	0.00	1.093	15.22	8988	12.69	10779
60	0.00	0.00	0.00	1.093	17.21	7950[a]	13.98	9780
90	0.00	0.00	0.00	1.093	19.26	7108	15.44	8861
120	0.00	0.00	0.00	1.093	21.31	6428	17.03	8037
167	0.00	0.00	0.00	1.093	24.27	5647	19.69	6954
212	0.00	0.00	0.00	1.093	25.62	5352	22.32	6136

[a]Design condition.

Note: **Calculations based on:** (1) NESC Heavy Loading District. (2) Tension Limits: a. Initial Loaded – 60% RBS @ 0°F; b. Initial Unloaded – 25% RBS @ 60°F; Final Unloaded – 15% RBS @ 60°F.

conductor tension is increased until the sag in one or more suspension spans reaches the appropriate stringing sags based on the ruling span for the line section. The calculation of stringing sags is based on the preceding sag equation.

Table 14.13 shows a typical stringing sag table for a 600-ft ruling span of Drake ACSR with suspension spans ranging from 400 to 700 ft and conductor temperatures of 20–100°F. All values in this stringing table are calculated from ruling span initial tensions, shown in Table 14.12 using the parabolic sag equation.

14.5 Line Design Sag-Tension Parameters

In laying out a transmission line, the first step is to survey the route and draw up a plan-profile of the selected right-of-way. The plan-profile drawings serve an important function in linking together

TABLE 14.13 Typical Sag and Tension Data 795 kcmil-37 Strand AAC "Arbutus," 300- and 1000-ft Spans

Conductor: Arbutus
795 kcmil-37 Strands AAC — **Span = 300 ft**
Area = 0.6245 in.^{2}
Creep ***is*** a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
30	0.00	9.00	0.05	1.122	3.56	3546	2.82	4479
30	0.00	0.00	0.00	0.746	2.91	2889	2.06	4075
60	0.00	0.00	0.00	0.746	4.03	2085[a]	2.80	2999
90	0.00	0.00	0.00	0.746	5.13	1638	3.79	2215
120	0.00	0.00	0.00	0.746	6.13	1372	4.86	1732
167	0.00	0.00	0.00	0.746	7.51	1122	6.38	1319
212	0.00	0.00	0.00	0.746	8.65	975	7.65	1101

[a] Design condition.

Conductor: Arbutus
795 kcmil-37 Strands AAC — **Span = 1000 ft**
Area = 0.6245 in.^{2}
Creep ***is*** a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
30	0.00	9.00	0.05	1.122	44.50	3185	42.85	3305
30	0.00	0.00	0.00	0.746	43.66	2158	41.71	2258
60	0.00	0.00	0.00	0.746	45.24	2085[a]	43.32	2175
90	0.00	0.00	0.00	0.746	46.76	2018	44.89	2101
120	0.00	0.00	0.00	0.746	48.24	1958	46.42	2033
167	0.00	0.00	0.00	0.746	50.49	1873	48.72	1939
212	0.00	0.00	0.00	0.746	52.55	1801	50.84	1860

[a] Design condition.

Note: **Calculations based on:** (1) NESC Light Loading District. (2) Tension Limits: a. Initial Loaded – 60% RBS @ 30°F; b. Initial Unloaded – 25% RBS @ 60°F; c. Final Unloaded – 15% RBS @ 60°F.

the various stages involved in the design and construction of the line. These drawings, prepared based on the route survey, show the location and elevation of all natural and man-made obstacles to be traversed by, or adjacent to, the proposed line. These plan-profiles are drawn to scale and provide the basis for tower spotting and line design work.

Once the plan-profile is completed, one or more estimated ruling spans for the line may be selected. Based on these estimated ruling spans and the maximum design tensions, sag-tension data may be calculated providing initial and final sag values. From this data, sag templates may be constructed to the same scale as the plan-profile for each ruling span, and used to graphically spot structures.

14.5.1 Catenary Constants

The sag in a ruling span is equal to the weight per unit length, w, times the span length, S, squared, divided by 8 times the horizontal component of the conductor tension, H. The ratio of conductor horizontal tension, H, to weight per unit length, w, is the catenary constant, H/w. For a ruling span sag-tension calculation using eight loading conditions, a total of 16 catenary constant values could be defined, one for initial and final tension under each loading condition.

Catenary constants can be defined for each loading condition of interest and are used in any attempt to locate structures. Some typical uses of catenary constants for locating structures are to avoid

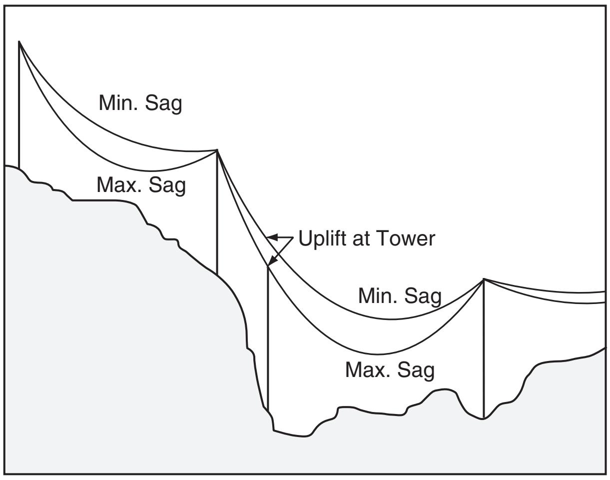


FIGURE 14.9 Conductor uplift.

overloading, assure ground clearance is sufficient at all points along the right-of-way, and minimize blowout or uplift under cold weather conditions. To do this, catenary constants are typically found for: (1) the maximum line temperature; (2) heavy ice and wind loading; (3) wind blowout; and (4) minimum conductor temperature. Under any of these loading conditions, the catenary constant allows sag calculation at any point within the span.

14.5.2 Wind Span

The maximum wind span of any structure is equal to the distance measured from center to center of the two adjacent spans supported by a structure. The wind span is used to determine the maximum horizontal force a structure must be designed to withstand under high wind conditions. Wind span is not dependent on conductor sag or tension, only on horizontal span length.

14.5.3 Weight Span

The weight span of a structure is a measure of the maximum vertical force a structure must be designed to withstand. The weight span is equal to the horizontal distance between the low points and the vertex of two adjacent spans. The maximum weight span for a structure is dependent on the loading condition being a minimum for heavy ice and wind load. When the elevations of adjacent structures are the same, the wind and weight spans are equal.

14.5.4 Uplift at Suspension Structures

Uplift occurs when the weight span of a structure is negative. On steeply inclined spans, the low point of sag may fall beyond the lower support. This indicates that the conductor in the uphill span is exerting a negative or upward force on the lower tower. The amount of this upward force is equal to the weight of the conductor from the lower tower to the low point in the sag. If the upward pull of the uphill span is greater than the downward load of the next adjacent span, actual uplift will be caused and the conductor will swing free of the tower. This usually occurs under minimum temperature conditions and must be dealt with by adding weights to the insulator suspension string or using a strain structure (Fig. 14.9).

14.5.5 Tower Spotting

Given sufficiently detailed plan-profile drawings, structure heights, wind/weight spans, catenary constants, and minimum ground clearances, structure locations can be chosen such that ground clearance is maintained and structure loads are acceptable. This process can be done by hand using a sag template, plan-profile drawing, and structure heights, or numerically by one of several commercial programs.

14.6 Conductor Installation

Installation of a bare overhead conductor can present complex problems. Careful planning and a thorough understanding of stringing procedures are needed to prevent damage to the conductor during the stringing operations. The selection of stringing sheaves, tensioning method, and measurement techniques are critical factors in obtaining the desired conductors sagging results. Conductor stringing and sagging equipment and techniques are discussed in detail in the *IEEE Guide to the Installation of Overhead Transmission Line Conductors,* IEEE Std. 524–1992. Some basic factors concerning installation are covered in this section. Because the terminology used for equipment and installation procedures for overhead conductors varies throughout the utility industry, a limited glossary of terms and equipment definitions excerpted from IEEE Std. 524–1992 is provided in the chapter appendix. A complete glossary is presented in the *IEEE Guide to the Installation of Overhead Transmission Line Conductors.*

14.6.1 Conductor Stringing Methods

There are two basic methods of stringing conductors, categorized as either slack or tension stringing. There are as many variations of these methods as there are organizations installing conductors. The selected method, however, depends primarily on the terrain and conductor surface damage requirements.

14.6.1.1 Slack or Layout Stringing Method

Slack stringing of conductor is normally limited to lower voltage lines and smaller conductors. The conductor reel(s) is placed on reel stands or "jack stands" at the beginning of the stringing location. The conductor is unreeled from the shipping reel and dragged along the ground by means of a vehicle or pulling device. When the conductor is dragged past a supporting structure, pulling is stopped and the conductor placed in stringing sheaves attached to the structure. The conductor is then reattached to the pulling equipment and the pull continued to the next structure.

This stringing method is typically used during construction of new lines in areas where the right-of-way is readily accessible to vehicles used to pull the conductor. However, slack stringing may be used for repair or maintenance of transmission lines where rugged terrain limits use of pulling and tensioning equipment. It is seldom used in urban areas or where there is any danger of contact with high-voltage conductors.

14.6.1.2 Tension Stringing

A tension stringing method is normally employed when installing transmission conductors. Using this method, the conductor is unreeled under tension and is not allowed to contact the ground. In a typical tension stringing operation, travelers are attached to each structure. A pilot line is pulled through the travelers and is used, in turn, to pull in heavier pulling line. This pulling line is then used to pull the conductor from the reels and through the travelers. Tension is controlled on the conductor by the tension puller at the pulling end and the bullwheel tension retarder at the conductor payout end of the installation. Tension stringing is preferred for all transmission installations. This installation method keeps the conductor off the ground, minimizing the possibility of surface damage and limiting problems at roadway crossings. It also limits damage to the right-of-way by minimizing heavy vehicular traffic.

14.6.2 Tension Stringing Equipment and Setup

Stringing equipment typically includes bullwheel or drum pullers for back-tensioning the conductor during stringing and sagging; travelers (stringing blocks) attached to every phase conductor and shield wire attachment point on every structure; a bullwheel or crawler tractor for pulling the conductor through travelers; and various other special items of equipment. Figure 14.10 illustrates a typical stringing and sagging setup for a stringing section and the range of stringing equipment required.

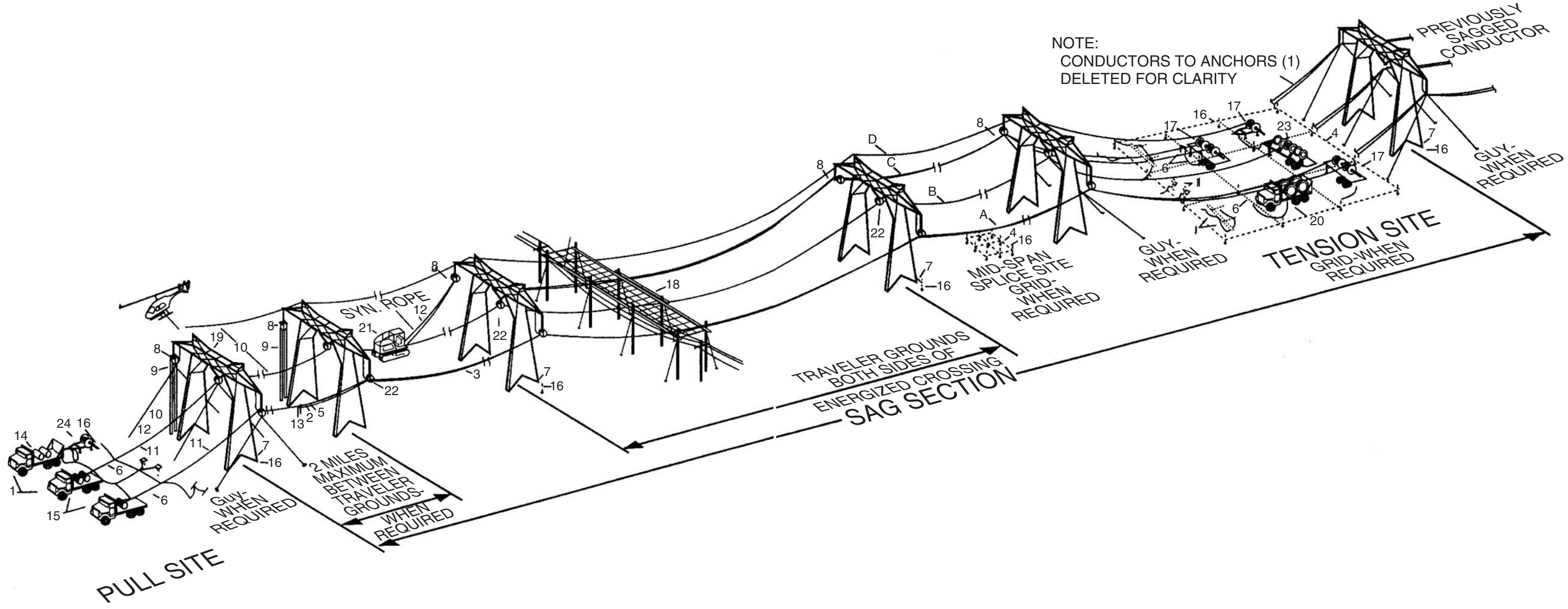


FIGURE 14.10 Tension stringing equipment setup.

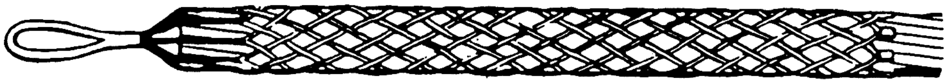


FIGURE 14.11 Basket grip pulling device.

Provision for conductor splicing during stringing must be made at tension site or midspan sites to avoid pulling splices through the travelers.

During the stringing operation, it is necessary to use proper tools to grip the strands of the conductor evenly to avoid damaging the outer layer of wires. Two basic types or categories of grips are normally used in transmission construction. The first is a type of grip referred to as a pocketbook, suitcase, bolted, etc., that hinges to completely surround the conductor and incorporates a bail for attaching to the pulling line. The second type is similar to a Chinese finger grip and is often referred to as a basket or "Kellem" grip. Such a grip, shown in Fig. 14.11, is often used because of its flexibility and small size, making it easily pulled through sheaves during the stringing operation. Whatever type of gripping device is used, a swivel should be installed between the pulling grip and pulling line or running board to allow free rotation of both the conductor and the pulling line.

A traveler consists of a sheave or pulley wheel enclosed in a frame to allow it to be suspended from structures or insulator strings. The frame must have some type of latching mechanism to allow insertion and removal of the conductor during the stringing operation. Travelers are designed for a maximum safe working load. Always ensure that this safe working load will not be exceeded during the stringing operation. Sheaves are often lined with neoprene or urethane materials to prevent scratching of conductors in high-voltage applications; however, unlined sheaves are also available for special applications.

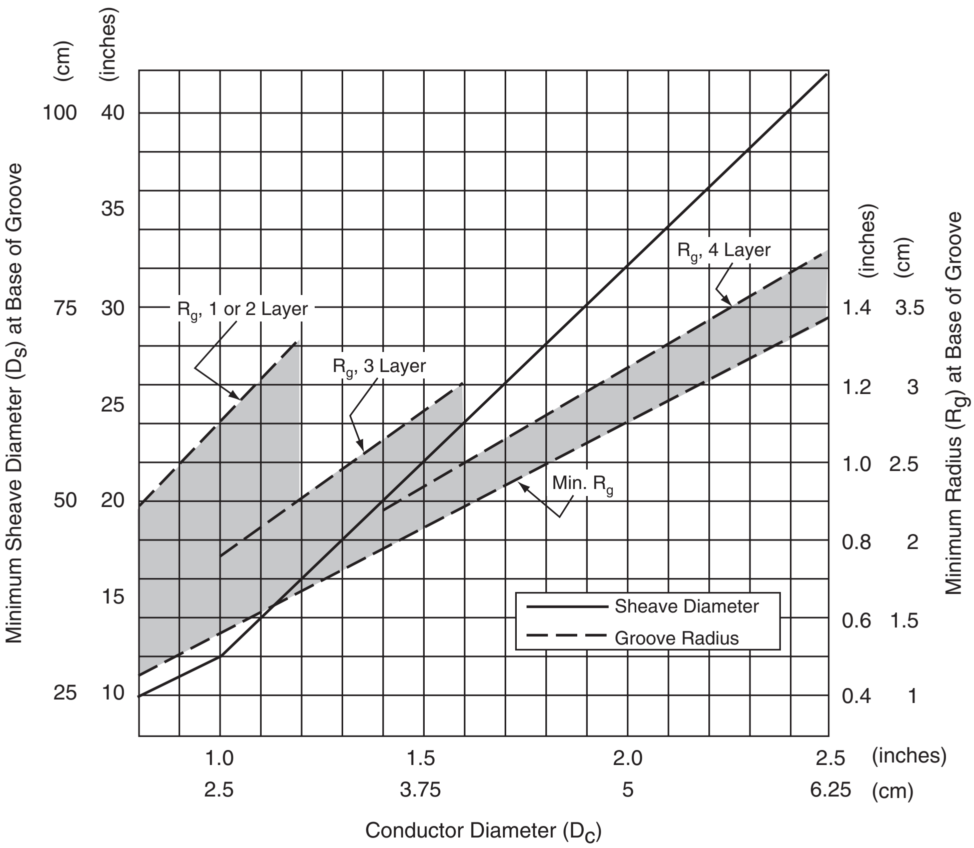


FIGURE 14.12 Recommended minimum sheave dimensions.

Travelers used in tension stringing must be free rolling and capable of withstanding high running or static loads without damage. Proper maintenance is essential. Very high longitudinal tension loads can develop on transmission structures if a traveler should "freeze" during tension stringing, possibly causing conductor and/or structure damage. Significant levels of rotation resistance will also yield tension differences between spans, resulting in incorrect sag.

Proper selection of travelers is important to assure that travelers operate correctly during tension stringing and sagging. The sheave diameter and the groove radius must be matched to the conductor.

Figure 14.12 illustrates the minimum sheave diameter for typical stringing and sagging operations. Larger diameter sheaves may be required where particularly severe installation conditions exist.

14.6.3 Sagging Procedure

It is important that the conductors be properly sagged at the correct stringing tension for the design ruling span. A series of several spans, a line section, is usually sagged in one operation. To obtain the correct sags and to insure the suspension insulators hang vertically, the horizontal tension in all spans must be equal. Figures 14.13 through 14.18 depict typical parabolic methods and computations required

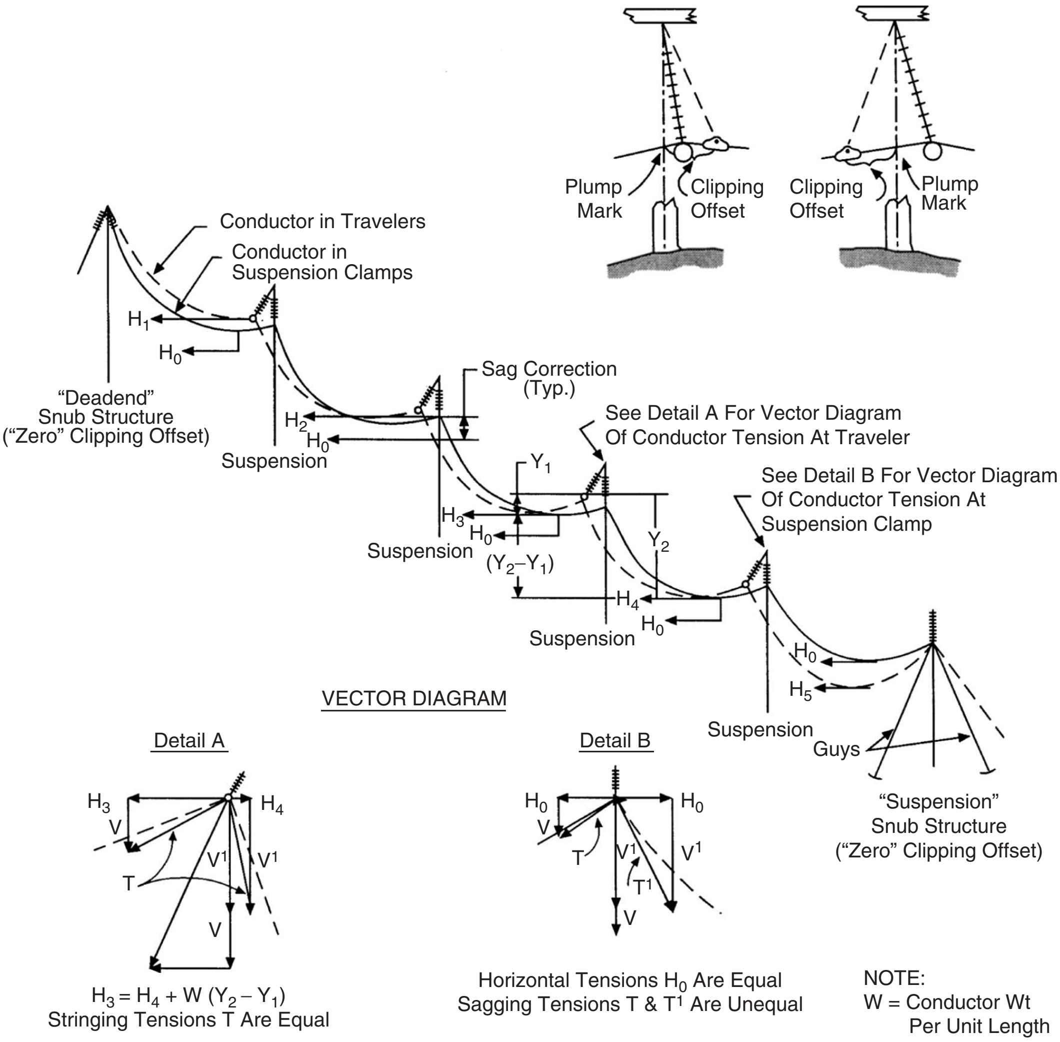


FIGURE 14.13 Clipping offset illustration.

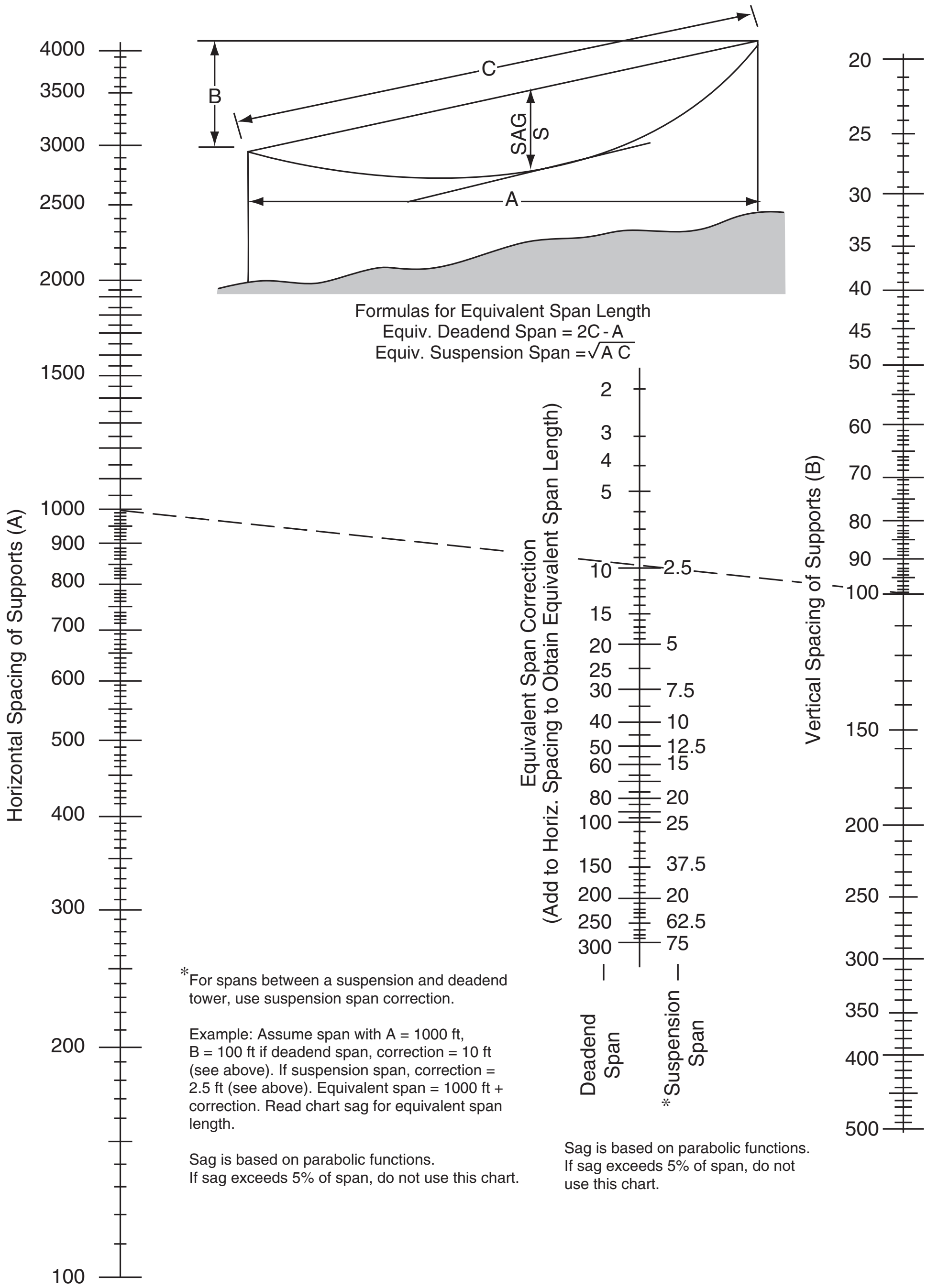


FIGURE 14.14 Nomograph for determining level span equivalents of non-level spans.

for sagging conductors. Factors that must be considered when sagging conductors are creep elongation during stringing and prestressing of the conductor.

Creep elongation during stringing: Upon completion of conductor stringing, a time of up to several days may elapse before the conductor is tensioned to design sag. Since the conductor tension during the stringing process is normally well below the initial sagging tension, and because the conductor remains in the stringing sheaves for only a few days or less, any elongation due to creep is neglected. The

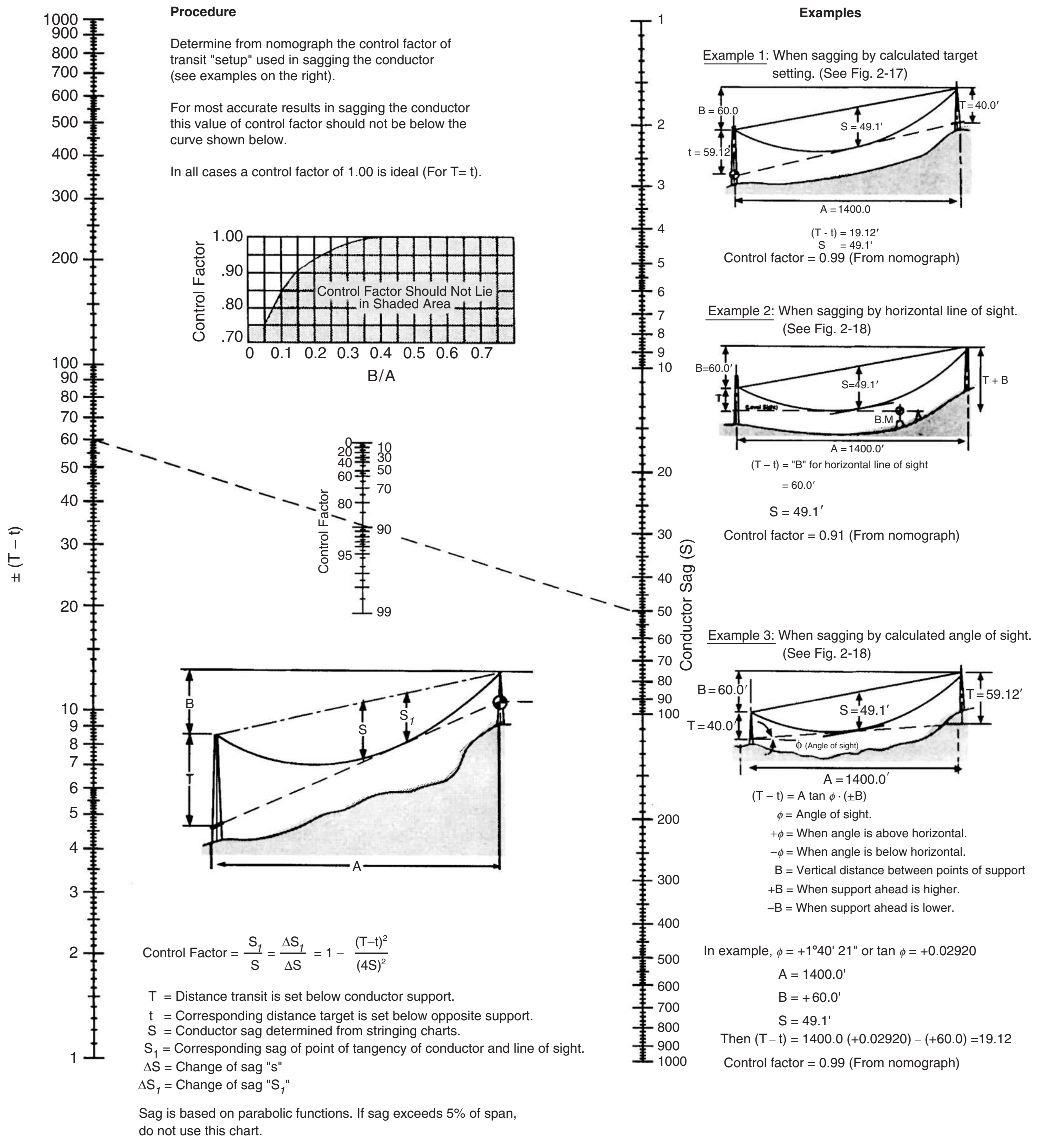
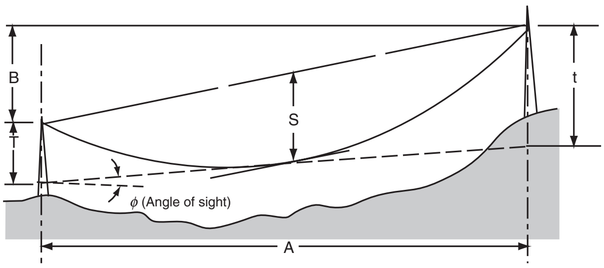


FIGURE 14.15 Nomograph for determining control factor for conductor sagging.

conductor should be sagged to the initial stringing sags listed in the sag tables. However, if the conductor tension is excessively high during stringing, or the conductor is allowed to remain in the blocks for an extended period of time, then the creep elongation may become significant and the sagging tables should be corrected prior to sagging.

Creep is assumed exponential with time. Thus, conductor elongation during the first day under tension is equal to elongation over the next week. Using creep estimation formulas, the creep strain can be estimated and adjustments made to the stringing sag tables in terms of an equivalent temperature. Also, should this become a concern, Southwire's Wire and Cable Technology Group will be happy to work with you to solve the problem.

Prestressing conductor: Prestressing is sometimes used to stabilize the elongation of a conductor for some defined period of time. The prestressing tension is normally much higher than the unloaded design tension for a conductor. The degree of stabilization is dependent upon the time maintained at the



METHOD 1: $\tan\phi = \dfrac{T \pm B - t}{A}$

METHOD 2: $\tan\phi = \dfrac{B + 2T - S(2+M)}{A}$

ϕ = Angle of sight
+ ϕ When angle is above horizontal
– ϕ When angle is below horizontal
t = Vertical distance below support to line of sight. (See Fig. 2-17).
T = Vertical distance below support for transit.
S = Sag
A = Horizontal distance between points of support - obtained from structure list or plan & profile
B = Vertical distance between points of support - obtained from plan & profile, tower site data sheets or field measurement.
+ B when support ahead is higher.
– B when support ahead is lower.
M = Determined from cure on Fig. 2-17.

EXAMPLES:
Given:

A = 1400.0'	S = 49.1' @ 60°F
B = +60.0'	S = 51.2' @ 90°F
T = 40.0'	T = 59.12' @ 60°F
	T = 63.76' @ 90°F

METHOD 1

$$\tan\phi = \frac{T \pm B - t}{A}$$

$$\tan\phi_{60°F} = \frac{40.0 - 60.0 - 59.12}{1400.0} = 0.02920$$

$$\phi_{60°F} = +1° \, 40'21''$$

$$\tan\phi_{90°F} = \frac{40.0 - 60.0 - 63.76}{1400.0} = 0.02589$$

$$\phi_{90°F} = +1° \, 28' \, 59''$$

$$\text{Change in angle } \phi \text{ for } 5°F = (1° \, 40' \, 21'' - 1° \, 28' \, 59'')\left(\frac{5}{30}\right) = 0° \, 1' \, 54''$$

METHOD 2

$$\tan\phi = \frac{B + 2T - S\,(2 + M)}{A}$$

$$\tan\phi_{60°F} = \frac{60.0 + (40.0)(2) - (49.1)\,(2{+}0.019)}{1400.0} = 0.02919$$

$$\phi_{60°F} = +1° \, 40' \, 19''$$

$$\tan\phi_{90°F} = \frac{60.0 + (40.0)\,(2) - (51.2)\,(2{+}0.027)}{1400.0} = 0.02587$$

$$\phi_{90°F} = +1° \, 28' \, 55''$$

$$\text{Change in angle } \phi \text{ for } 5° F = (1° \, 40' \, 19'' - 1° \, 28' \, 55'')\left(\frac{5}{30}\right) = 0° \, 1' \, 54''$$

Sag is based on parabolic functions. If sag exceeds 5% of span, do not use this chart.

FIGURE 14.16 Conductor sagging by calculated angle of sight.

prestress tension. After prestressing, the tension on the conductor is reduced to stringing or design tension limits. At this reduced tension, the creep or plastic elongation of the conductor has been slowed, reducing the permanent elongation due to strain and creep for a defined period of time. By tensioning a conductor to levels approaching 50% of its breaking strength for times on the order of a day, creep elongation will be temporarily halted (Cahill, 1973). This simplifies concerns about creep during subsequent installation but presents both equipment and safety problems.

14.6.3.1 Sagging by Stopwatch Method

A mechanical pulse imparted to a tensioned conductor moves at a speed proportional to the square root of tension divided by weight per unit length. By initiating a pulse on a tensioned conductor and measuring the time required for the pulse to move to the nearest termination, the tension, and thus

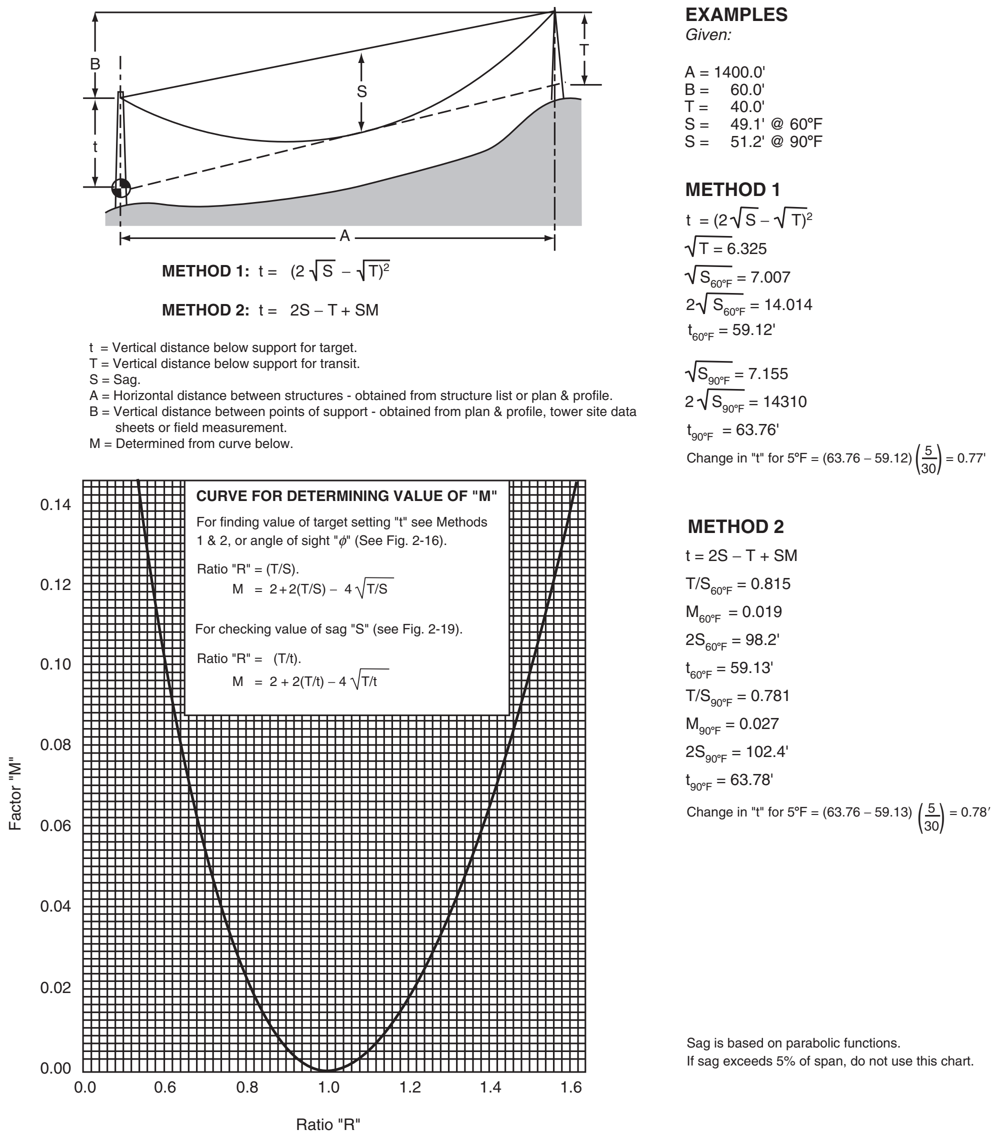


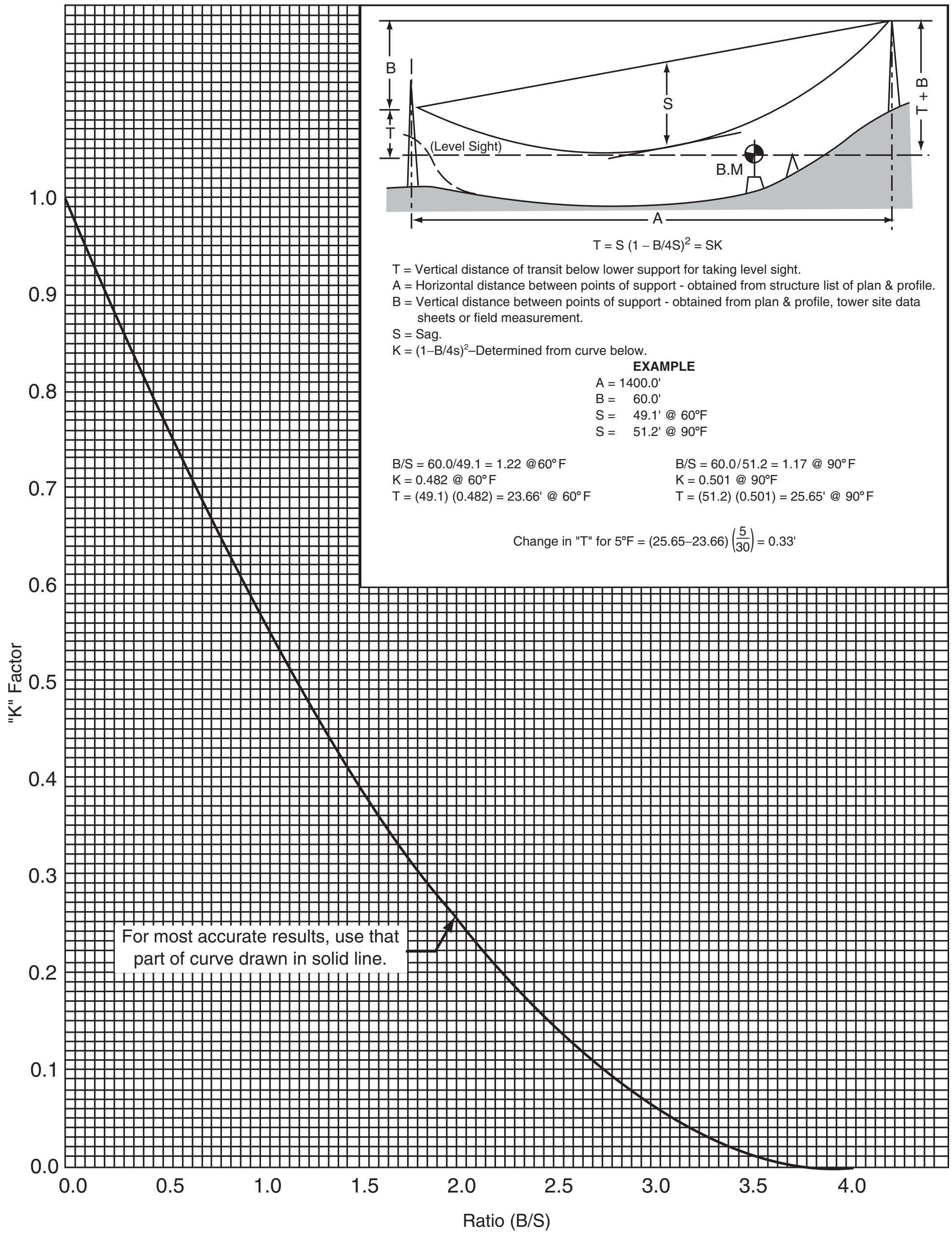
FIGURE 14.17 Conductor sagging by calculated target method.

the sag of the conductor, can be determined. This stopwatch method (Overend and Smith) has come into wide use even for long spans and large conductors.

The conductor is struck a sharp blow near one support and the stopwatch is started simultaneously. A mechanical wave moves from the point where the conductor was struck to the next support point at which it will be partially reflected. If the initiating blow is sharp, the wave will travel up and down the span many times before dying out. Time-sag tables such as the one shown in Table 14.14 are available from many sources. Specially designed sagging stopwatches are also available.

The reflected wave can be detected by lightly touching the conductor but the procedure is more likely to be accurate if the wave is both initiated and detected with a light rope over the conductor. Normally, the time for the return of the 3rd or 5th wave is monitored.

Traditionally, a transit sagging method has been considered to be more accurate for sagging than the stopwatch method. However, many transmission-line constructors use the stopwatch method exclusively, even with large conductors.



Sag is based on parabolic functions. If sag exceeds 5% of span, do not use this chart.

FIGURE 14.18 Conductor sagging by horizontal line of sight.

14.6.3.2 Sagging by Transit Methods

IEEE Guide Std. 524–1993 lists three methods of sagging conductor with a transit: "Calculated Angle of Sight," "Calculated Target Method," and "Horizontal Line of Sight." The method best suited to a particular line sagging situation may vary with terrain and line design.

TABLE 14.14 Typical Sag and Tension Data 795 kcmil-37 Strand AAC "Arbutus," 300- and 1000-ft Spans

Conductor: Arbutus
795 kcmil-37 Strands AAC — **Span = 300 ft**
Area = 0.6245 in.^{2}
Creep *is* a factor

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.125	3.97	6033	3.75	6383
32	0.50	0.00	0.00	1.696	4.35	4386	3.78	5053
−20	0.00	0.00	0.00	0.746	1.58	5319	1.39	6055
0	0.00	0.00	0.00	0.746	2.00	4208	1.59	5268
30	0.00	0.00	0.00	0.746	2.91	2889	2.06	4075
60	0.00	0.00	0.00	0.746	4.03	2085[a]	2.80	2999
90	0.00	0.00	0.00	0.746	5.13	1638	3.79	2215
120	0.00	0.00	0.00	0.746	6.13	1372	4.86	1732
167	0.00	0.00	0.00	0.746	7.51	1122	6.38	1319
212	0.00	0.00	0.00	0.746	8.65	975	7.65	1101

[a]Design condition.

Conductor: Arbutus
795 kcmil-37 Strands AAC — **Span = 1000 ft**
Area = 0.6245 in.^{2}
Creep *is* a factor — *NESC Heavy Loading District*

					Final		Initial	
Temp, °F	Ice, in.	Wind, lb/ft^2	K, lb/ft	Weight, lb/ft	Sag, ft	Tension, lb	Sag, ft	Tension, lb
0	0.50	4.00	0.30	2.125	45.11	59.53	44.50	6033
32	0.50	0.00	0.00	1.696	45.80	4679	44.68	4794
−20	0.00	0.00	0.00	0.746	40.93	2300	38.89	2418
0	0.00	0.00	0.00	0.746	42.04	2240	40.03	2350
30	0.00	0.00	0.00	0.746	43.66	2158	41.71	2258
60	0.00	0.00	0.00	0.746	45.24	2085[a]	43.32	2175
90	0.00	0.00	0.00	0.746	46.76	2018	44.89	2101
120	0.00	0.00	0.00	0.746	48.24	1958	46.42	2033
167	0.00	0.00	0.00	0.746	50.49	1873	48.72	1939
212	0.00	0.00	0.00	0.746	52.55	1801	50.84	1860

[a]Design condition.

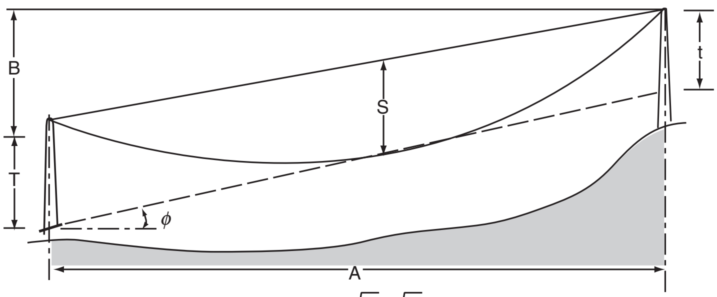
Note: **Calculations based on:** (1) NESC Light Loading District. (2) Tension Limits: a. Initial Loaded – 60% RBS @ 0°F; b. Initial Unloaded – 25% RBS @ 60°F; c. Final Unloaded – 15% RBS @ 60°F.

14.6.3.3 Sagging Accuracy

Sagging a conductor during construction of a new line or in the reconductoring of a old line involves many variables that can lead to a small degree of error. IEEE Std. 524–1993 suggests that all sags be within 6 in. of the stringing sag values. However, aside from measurement errors during sagging, errors in terrain measurement and variations in conductor properties, loading conditions, and hardware installation have led some utilities to allow up to 3 ft of margin in addition to the required minimum ground clearance.

14.6.3.4 Clipping Offsets

If the conductor is to be sagged in a series of suspension spans where the span lengths are reasonably close and where the terrain is reasonably level, then the conductor is sagged using conventional stringing sag tables and the conductor is simply clipped into suspension clamps that replace the travelers. If the



METHOD 1: $S = \left(\dfrac{\sqrt{T}+\sqrt{t}}{2}\right)^2$

METHOD 2: $S = \dfrac{B}{2} + \dfrac{t}{2} - \dfrac{tM}{8}$

S = Sag
t = Vertical distance below support to line of sight.
= T ± B – A tan ϕ when angle ϕ is above horizontal.
= T± B + A tan ϕ when angle ϕ is below horizontal.
T = Vertical distance below support for transit.
B = Vertical distance between points of support - obtanied from plan & profile, tower site data sheets or field measurement.
+ B when support ahead is higher.
– B when support ahead is lower.
A = Horizontal distance between points of support - obtained from structure list or plan & profile
ϕ = Angle of sight
M = Determined from cure on Fig. 2.17.

EXAMPLES

Given:

A = 1400.0'
B = 60.0'
T = 40.0'
ϕ = +1°40′21″ @ 60°F
(Field Measured)

METHOD 1

$S = \left(\dfrac{\sqrt{T}+\sqrt{t}}{2}\right)^2$

t = 40.0 + 60.0 – 1400.0 tan 1° 40' 21"

= 59.12'

$\sqrt{t}$ = 7.689

$\sqrt{T}$ = 6.325

$S_{60°F}$ = 49.1'

METHOD 2

Note: When using Method 2, value, "T" should lie between 3/4 "S" & 4/3 "S"

$S = \dfrac{B}{2} + \dfrac{t}{2} - \dfrac{tM}{8}$

t = 59.12'

t/2 = 29.56'

T/2 = 20.0″

M = 0.061

$S_{60°F} = 20.0 + 29.56 - \dfrac{(59.12)\,(0.061)}{8}$

$S_{60°F}$ = 49.1'

Sag is based on parabolic functions. if sag exceeds 5% of span, do not use this chart.

FIGURE 14.19 Conductor sagging for checking sag S.

conductor is to be sagged in a series of suspension spans where span lengths vary widely or more commonly, where the terrain is steep, then clipping offsets may need to be employed in order to yield vertical suspension strings after installation.

Clipping offsets are illustrated in Fig. 14.19, showing a series of steeply inclined spans terminated in a "snub" structure at the bottom and a "deadend" structure at the top. The vector diagram illustrates a balance of total conductor tension in the travelers but an imbalance in the horizontal component of tension.

14.7 Defining Terms

Block—A device designed with one or more single sheaves, a wood or metal shell, and an attachment hook or shackle. When rope is reeved through two of these devices, the assembly is commonly referred to as a *block and tackle.* A *set of 4s* refers to a block and tackle arrangement utilizing two 4-inch double-sheave blocks to obtain four load-bearing lines. Similarly, a *set of 5s* or a *set of 6s* refers to the same number of load bearing lines obtained using two 5-inch or two 6-inch double-sheave blocks, respectively.

Synonyms: set of 4s, set of 5s, set of 6s.

Bullwheel—A wheel incorporated as an integral part of a bullwheel puller or tensioner to generate pulling or braking tension on conductors or pulling lines, or both, through friction. A puller or tensioner normally has one or more pairs arranged in tandem incorporated in its design. The physical size of the wheels will vary for different designs, but 17-in. (43 cm) face widths and diameters of 5 ft (150 cm) are common. The wheels are power driven or retarded and lined with single- or multiple-groove neoprene or urethane linings. Friction is accomplished by reeving the pulling line or conductor around the groove of each pair.

Clipping-in—The transferring of sagged conductors from the traveler to their permanent suspension positions and the installing of the permanent suspension clamps.

Synonyms: clamping, clipping.

Clipping offset—A calculated distance, measured along the conductor from the plum mark to a point on the conductor at which the center of the suspension clamp is to be placed. When stringing in rough terrain, clipping offset may be required to balance the horizontal forces on each suspension structure.

Grip, conductor—A device designed to permit the pulling of conductor without splicing on fittings, eyes, etc. It permits the pulling of a *continuous* conductor where threading is not possible. The designs of these grips vary considerably. Grips such as the Klein (Chicago) and Crescent utilize an open-sided rigid body with opposing jaws and swing latch. In addition to pulling conductors, this type is commonly used to tension guys and, in some cases, pull wire rope. The design of the come-along (pocketbook, suitcase, four bolt, etc.) incorporates a bail attached to the body of a clamp which folds to completely surround and envelope the conductor. Bolts are then used to close the clamp and obtain a grip.

Synonyms: buffalo, Chicago grip, come-along, Crescent, four bolt, grip, Klein, pocketbook, seven bolt, six bolt, slip-grip, suitcase.

Line, pilot—A lightweight line, normally synthetic fiber rope, used to pull heavier pulling lines which in turn are used to pull the conductor. Pilot lines may be installed with the aid of finger lines or by helicopter when the insulators and travelers are hung.

Synonyms: lead line, leader, P-line, straw line.

Line, pulling—A high-strength line, normally synthetic fiber rope or wire rope, used to pull the conductor. However, on reconstruction jobs where a conductor is being replaced, the old conductor often serves as the pulling line for the new conductor. In such cases, the old conductor must be closely examined for any damage prior to the pulling operations.

Synonyms: bull line, hard line, light line, sock line.

Puller, bullwheel—A device designed to pull pulling lines and conductors during stringing operations. It normally incorporates one or more pairs of urethane- or neoprene-lined, power-driven, single- or multiple-groove bullwheels where each pair is arranged in tandem. Pulling is accomplished by friction generated against the pulling line which is reeved around the grooves of a pair of the bullwheels. The puller is usually equipped with its own engine which drives the bullwheels mechanically, hydraulically, or through a combination of both. Some of these devices function as either a puller or tensioner.

Synonym: puller.

Puller, drum—A device designed to pull a conductor during stringing operations. It is normally equipped with its own engine which drives the drum mechanically, hydraulically, or through a combination of both. It may be equipped with synthetic fiber rope or wire rope to be used as the pulling line. The pulling line is payed out from the unit, pulled through the travelers in the sag section and attached to the conductor. The conductor is then pulled in by winding the pulling line back onto the drum. This unit is sometimes used with synthetic fiber rope acting as a pilot line to pull heavier pulling lines across canyons, rivers, etc.

Synonyms: hoist, single drum hoist, single drum winch, tugger.

Puller, reel—A device designed to pull a conductor during stringing operations. It is normally equipped with its own engine which drives the supporting shaft for the reel mechanically, hydraulically, or through a combination of both. The shaft, in turn, drives the reel. The application of this unit is essentially the same as that for the drum puller previously described. Some of these devices function as either a puller or tensioner.

Reel stand—A device designed to support one or more reels and having the possibility of being skid, trailer, or truck mounted. These devices may accommodate rope or conductor reels of varying sizes and are usually equipped with reel brakes to prevent the reels from turning when pulling is stopped. They are used for either slack or tension stringing. The designation of reel trailer or reel truck implies that the trailer or truck has been equipped with a reel stand (jacks) and may serve as a reel transport or *payout* unit, or both, for stringing operations. Depending upon the sizes of the reels to be carried, the transporting vehicles may range from single-axle trailers to semi-trucks with trailers having multiple axles.

Synonyms: reel trailer, reel transporter, reel truck.

Running board—A pulling device designed to permit stringing more than one conductor simultaneously with a single pulling line. For distribution stringing, it is usually made of lightweight tubing with the forward end curved gently upward to provide smooth transition over pole cross-arm rollers. For transmission stringing, the device is either made of sections hinged transversely to the direction of pull or of a hard-nose rigid design, both having a flexible pendulum tail suspended from the rear. This configuration stops the conductors from twisting together and permits smooth transition over the sheaves of bundle travelers.

Synonyms: alligator, bird, birdie, monkey tail, sled.

Sag section—The section of line between snub structures. More than one sag section may be required in order to properly sag the actual length of conductor which has been strung.

Synonyms: pull, setting, stringing section.

Site, pull—The location on the line where the puller, reel winder, and anchors (snubs) are located. This site may also serve as the pull or tension site for the next sag section.

Synonyms: reel setup, tugger setup.

Site, tension—The location on the line where the tensioner, reel stands and anchors (snubs) are located. This site may also serve as the pull or tension site for the next sag section.

Synonyms: conductor payout station, payout site, reel setup.

Snub structure—A structure located at one end of a sag section and considered as a *zero* point for sagging and clipping offset calculations. The section of line between two such structures is the sag section, but more than one sag section may be required in order to sag properly the actual length of conductor which has been strung.

Synonyms: *0* structure, zero structure.

Tensioner, bullwheel—A device designed to hold tension against a pulling line or conductor during the stringing phase. Normally, it consists of one or more pairs of urethane- or neoprene-lined, power braked, single- or multiple-groove bullwheels where each pair is arranged in tandem. Tension is accomplished by friction generated against the conductor which is reeved around the grooves of a pair of the bullwheels. Some tensioners are equipped with their own engines which retard the bullwheels mechanically, hydraulically, or through a combination of both. Some of these devices function as either a puller or tensioner. Other tensioners are only equipped with friction-type retardation.

Synonyms: retarder, tensioner.

Tensioner, reel—A device designed to generate tension against a pulling line or conductor during the stringing phase. Some are equipped with their own engines which retard the supporting shaft for the reel mechanically, hydraulically, or through a combination of both. The shaft, in turn, retards the reel. Some of these devices function as either a puller or tensioner. Other tensioners are only equipped with friction type retardation.

Synonyms: retarder, tensioner.

Traveler—A sheave complete with suspension arm or frame used separately or in groups and suspended from structures to permit the stringing of conductors. These devices are sometimes bundled with a center drum or sheave, and another traveler, and used to string more than one conductor simultaneously. For protection of conductors that should not be nicked or scratched, the sheaves are often lined with nonconductive or semiconductive neoprene or with nonconductive urethane. Any one of these materials acts as a padding or cushion for the conductor as it passes over the sheave. Traveler grounds must be used with lined travelers in order to establish an electrical ground.

Synonyms: block, dolly, sheave, stringing block, stringing sheave, stringing traveler.

Winder reel—A device designed to serve as a recovery unit for a pulling line. It is normally equipped with its own engine which drives a supporting shaft for a reel mechanically, hydraulically, or through a combination of both. The shaft, in turn, drives the reel. It is normally used to rewind a pulling line as it leaves the bullwheel puller during stringing operations. This unit is not intended to serve as a puller, but sometimes serves this function where only low tensions are involved.

Synonyms: take-up reel.

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