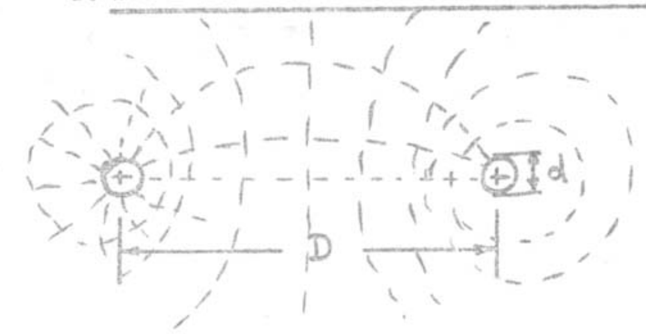
Transmission Line Parameters Lecture #1

chapters 3 and 4 stevenson

I. L & C PER UNIT LENGTH OF TWO PARALLEL WIRES



If $\frac{D}{d}$ is large (say $\frac{D}{d} \geq 10$), we can assume:

1. Proximity effects are negligible, i.e. the currents will be uniformly distributed over the cross section areas of the wires if we neglect the skin effect.

2. The magnetic field around each conductor is made of concentric circles.

3. In this case we are also neglecting ground effects. (i.e. assuming $h \gg D$)

4. We are assuming solid round conductors.

Internal Inductance

$$\oint H_x \, ds = I_x \qquad (1)$$

$$\therefore\ 2\pi x H_x = I_x \qquad (2)$$

$$I_x = \frac{\pi x^2}{\pi r^2} I \qquad (3)$$

From (2) & (3)

$$H_x = \frac{x}{2\pi r^2} I \qquad \text{amp-turn/meter}$$

or

$$B_x = \frac{x}{2\pi r^2} \mu I \qquad \text{weber/met}^2$$

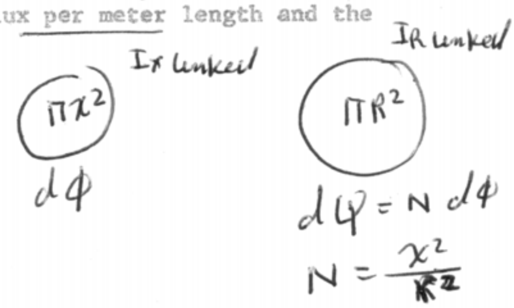
11.6

and $d\phi = B_x da$ weber

$$= \frac{x}{2\pi r^2} \mu I \, dx \quad (da = dx \circ 1) \quad \text{weber/meter length}$$

Flus linkage $d\psi$ per meter length, which is caused by the flux in the tubular element, is the product of the flux per meter length and the fraction of the current linked

$$d\psi = \frac{\pi x^2}{\pi r^2} d\phi = \frac{\mu I x^3}{2\pi r^4} dx$$



∴ Flux linkages inside conductor:

$$\psi_{int} = \int_0^r \frac{\mu I x^3}{2\pi r^4} dx$$

$$= \frac{\mu I}{8\pi} \text{ weber-turn/met length.}$$

and $L_{int} = \frac{\mu}{8\pi}$ henry/met length

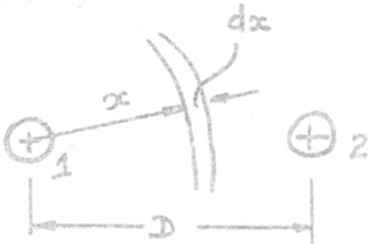
But $\mu = 4\pi \, 10^{-7}$ henry/met length

∴ $\boxed{L_{int} = \tfrac{1}{2} \times 10^{-7} \text{ henry/met}}$

External Inductance:

At a point x met, from center of conductor 1:

$$2\pi x \, H_{1x} = I_1$$



or

$$H_{1x} = \frac{I_1}{2\pi x} \quad \text{amp-turn/met}$$

$$B_{1x} = \frac{\mu I_1}{2\pi x} \quad \text{webers/met}^2$$

$$d\phi_1 = \frac{\mu I_1}{2\pi x} dx \quad \text{webers/met length}$$

$$\therefore \quad \psi_{1ext} = \int_{r_1}^{D} \frac{\mu I_1}{2\pi x} dx = \frac{\mu I_1}{2\pi} \ln \frac{D}{r_1} \text{ amp turn/met length}$$

or

$$L_{1ext} = \frac{\mu}{2\pi} \ln \frac{D}{r_1} \text{ Henry/met length}$$

$$\boxed{L_{1ext} = 2 \times 10^{-7} \ln \frac{D}{r_1} \text{ Henry/met length}}$$

$\therefore$ Total inductance per conductor:

$$L_1 = L_{1int} + L_{1ext}$$

$$= \tfrac{1}{2} \times 10^{-7} + 2 \times 10^{-7} \ln \frac{D}{r_1}$$

$$= 2 \times 10^{-7} \left(\tfrac{1}{4} + \ln \frac{D}{r_1}\right)$$

$$= 2 \times 10^{-7} \left(\ln \epsilon^{\frac{1}{4}} + \ln \frac{D}{r_1}\right)$$

$$= 2 \times 10^{-7} \ln \frac{D}{r_1 \epsilon^{-\frac{1}{4}}}$$

$$= 2 \times 10^{-7} \ln \frac{D}{r_1'} \text{ henry/met}$$

where

$$r_1' = \epsilon^{-\frac{1}{4}} r_1$$

$$= .7788\, r_1$$

$$= \text{G.M.R. of conductor 1}$$

Total inductance of conductor 1 = $2 \times 10^{-7} \ln \frac{D}{r_1'}$ Henry/met

$$= .7411 \text{ Log } \frac{D}{r_1'} \quad \text{mh/mile}$$

Similarly total inductance for conductor 2

$$L_2 = 2 \times 10^{-7} \ln \frac{D}{r_2'} \text{ Henry/met length}$$

$\therefore$ Total inductance for 2 wire circuit

$$L = L_1 + L_2$$

$$= 2 \times 10^{-7} \left(\ln \frac{D}{r_1'} + \ln \frac{D}{r_2'}\right)$$

$$= 2 \times 10^{-7} \ln \frac{D^2}{r_1' r_2'}$$

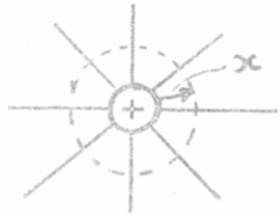
$$= 4 \times 10^{-7} \ln \frac{D}{\sqrt{r_1' r_2'}}$$

If $r_1 = r_2$:

$\therefore$ Total circuit inductance = $4 \times 10^{-7} \ln \frac{D}{r'}$ Henry/met length

$$= 2 \times .7411 \log \frac{D}{r'} \text{ mh/mile}$$

Electric Field of a Long, Straight, Circular Conductor:



Using the previous assumptions, the electric flux around the conductor will be radial and if we assume high conductivity, there will be no internal flux, i.e. the electric charge will be uniformly distributed on the cylindrical surface.

$\therefore$ electric flux density at a point at dist. x from the center

$$D_1 = \frac{q_1}{2\pi x} \text{ coulombs/met}^2$$

and

$$E_1 = \frac{q_1}{2\pi x k} \text{ volts/met length}$$

where k = permittivity

$= 8.85 \times 10^{-12}$ farad/met.

The Voltage Between Two Parallel Conductors:

$$v_{12} = \int_{r_1}^{D} E_1 dr + \int_{D}^{r_2} E_2 dr$$

$$= \frac{q_1}{2\pi k} \ln \frac{D}{r_1} + \frac{q_2}{2\pi k} \ln \frac{r_2}{D}$$

But $q_1 = -q_2 = q$

$$\therefore v_{12} = \frac{q}{2\pi k} \left(\ln \frac{D}{r_1} - \ln \frac{r_2}{D}\right)$$

$$= \frac{q}{2\pi k} \ln \frac{D^2}{r_1 r_2}$$

Capacitance of a Two-Wire Line:

$$C_{12} = \frac{q}{v_{12}}$$

$$= \frac{2\pi k}{2 \ln \frac{D}{r_1 r_2}} \quad \text{farads/met length}$$

if $r_1 = r_2$

Total Circuit Capacitance $= \frac{.0388}{2 \log D/r}$ μfarad/mile

Capacitance of one conductor to neutral $= \frac{.0388}{\log D/r}$ μf/mile

PROBLEMS (Reference: William D. Stevenson, Jr., ELEMENTS OF POWER SYSTEM ANALYSIS, McGraw-Hill, 1962)

2.1 1. A hollow cylindrical conductor has an outside diameter of 1.100 in. and a wall thickness of 0.130 in. Find the flux density at a distance of 0.485 in. from the center of the conductor when the current is 500 amp. Neglect the effect of the return circuit.

2.2 2. Derive the formula for the internal inductance in henrys per meter of a hollow conductor having an inside radius r_1 and an outside radius r_2. In what units should r_1 and r_2 be expressed?

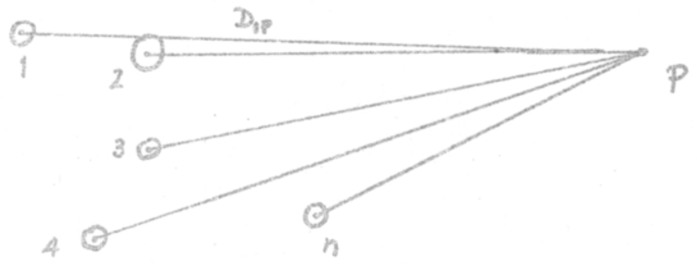
2.4 3. Compute the 60-cycle inductive reactance at 1 ft spacing in ohms per mile for the hollow conductor whose dimensions are given in Prob. 1.

4. Derive a formula for the capacitance between the single inner conductor and the concentric outer sheath of a power cable. Assume that the radius of the inner conductor is a and that the inner radius of the sheath is b. Also derive a formula for the inductance.

5. A single-conductor power cable has a conductor of No. 2 solid copper. Paper insulation separating the conductor from the concentric lead sheath has a thickness of 3/32 in. and a relative permittivity of 3.7. The thickness of the lead sheath is 5/64 in. Find the inductive and capacitive reactance per mile between the inner conductor and the lead sheath at 60 c.p.s.

II. L & C PER UNIT LENGTH OF n PARALLEL WIRES

Flux Linkages of One Conductor in a Group:



Cross-Sectional of n parallel conductors carrying currents whose sum is zero. Point P is remote from conductors.

Flux linkage ψ_{1P1} of conductor 1 due to I_1 including internal flux linkage but excluding all flux beyond point P:

$$\psi_{1P1} = 2 \times 10^{-7}\ I_1\ \ln \frac{D_{1P}}{r_1'} \text{ weber-turns/mt}$$

Flux linkage ψ_{1P2} with conductor 1 due to I_2, but excluding flux beyond point P:

$$\psi_{1P2} = \int_{D_{21}}^{D_{2P}} \frac{\mu I_2}{2\pi x}\, dx = 2 \times 10^{-7}\ I_2\ \ln \frac{D_{2P}}{D_{21}} \text{ weber-turns/mt}$$

Flux linkage ψ_{1P} with conductor 1 due to all conductors, but excluding flux beyond P:

$$\psi_{1P} = 2 \times 10^{-7} \left[I_1\ \ln \frac{D_{1P}}{r_1'} + I_2\ \ln \frac{D_{2P}}{D_{21}} + \ldots + I_n\ \ln \frac{D_{nP}}{D_{n1}} \right]$$

$$= 2 \times 10^{-7} \left[I_1\ \ln \frac{1}{r_1'} + I_2\ \ln \frac{1}{D_{21}} + \ldots + I_n\ \ln \frac{1}{D_{n1}} + I_1 \ln D_{1p} + I_2\ \ln D_{2P} + \ldots + I_n\ \ln D_{nP} \right]$$

As $P \to \infty$; $\ln D_{1P} = \ln D_{2P} = \ldots = \ln D_{nP} = K$

$$\therefore \psi_{1P} = 2 \times 10^{-7} \left[I_1 \ln \frac{1}{r_1'} + I_2 \ln \frac{1}{D_{21}} + \ldots + I_n \ln \frac{1}{D_{n1}} + (I_1 + I_2 + \ldots + I_n) \right.$$

But $I_1 + I_2 + \ldots + I_n = 0$

$$\therefore \psi_1 = 2 \times 10^{-7} \left(I_1 \ln \frac{1}{r_1'} + I_2 \ln \frac{1}{D_{21}} + \ldots + I_n \ln \frac{1}{D_{n1}} \right)$$

In general, flux linkage of conductor j which is one of n parallel conductors carrying currents whose sum is zero is:

$$\psi_j = 2 \times 10^{-7} \sum_{i=1}^{n} I_i \ln \frac{1}{D_{ij}} \text{ weber-turns/mt}$$

where D_{jj} = G.M.R. of conductor j

= $.7788\, r_j$ for solid round conductor.

Inductance Matrix of n conductor:

The above flux linkage equation can be written in matrix form as follows:

$$\begin{array}{c} \\ 1 \\ 2 \\ 3 \\ \vdots \\ n \end{array}
\begin{bmatrix} \psi_1 \\ \psi_2 \\ \Psi_3 \\ \\ \psi_n \end{bmatrix}
=
\begin{array}{c} \\ 1 \\ 2 \\ 3 \\ \\ \\ \end{array}
\begin{array}{c} \begin{array}{cccc} 1 & 2 & 3 & n \end{array} \\
\begin{bmatrix} L_{11} & L_{12} & L_{13} & L_{1n} \\ L_{21} & L_{22} & L_{23} & L_{2n} \\ L_{31} & L_{32} & L_{33} & \\ & & & \\ L_{n1} & L_{n2} & & L_{nn} \end{bmatrix} \end{array}
\begin{array}{c} 1 \\ 2 \\ \\ \\ n \end{array}
\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ \\ I_2 \end{bmatrix}$$

where: $L_{ii} = 2 \times 10^{-7} \ln \frac{1}{r_1'}$ henry/mt & $L_{ij} = L_{ji} = 2 \times 10^{-7} \ln \frac{1}{D_{ij}}$ henry/mt

|| = self inductance of conductor i

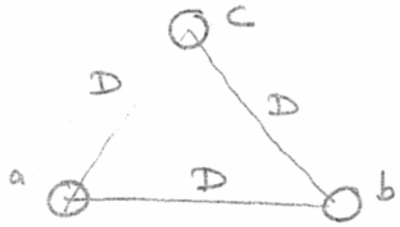
also called L_{self}

↓ = mutual inductance between conductors i & j

L_{mutual}

Special Cases of Inductances:

Case (1): Inductance of a 3-phase line with equilateral spacing



Flux linkages of conductor a is:

$$\psi_a = 2 \times 10^{-7} \left[I_a \ln \frac{1}{r'} + I_b \ln \frac{1}{D} + I_c \ln \frac{1}{D} \right]$$

$$= 2 \times 10^{-7} \left[I_a \ln \frac{1}{r'} + (I_b + I_c) \ln \frac{1}{D} \right]$$

But $I_b + I_c = -I_a$

Then:

$$\therefore \psi_a = 2 \times 10^{-7} \left[I_a \left(\ln \frac{1}{r'} - \ln \frac{1}{D}\right) \right]$$

$$= 2 \times 10^{-7} I_a \ln \frac{D}{r'} \text{ weber-turns/mt}$$

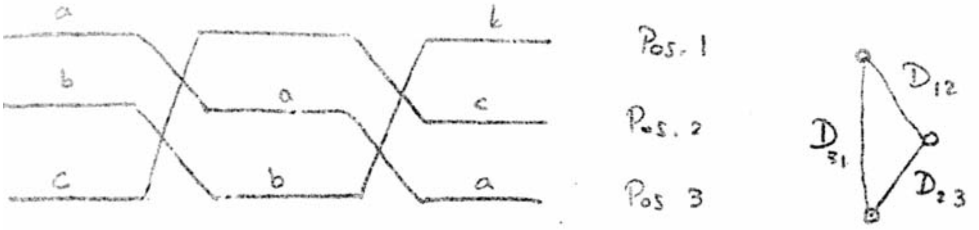
$$\therefore L_a = 2 \times 10^{-7} \ln \frac{D}{r'} \text{ henrys/mt}$$

or $L_a = .7411 \log_{10} \frac{D}{r'}$ mh/mile

and due to symmetry, $L_a = L_b = L_c$

Note: $L_a = L_b = L_c = L_{ph}$ = equivalent inductance per phase and includes both the self and mutual effects. ($L_{ph} = L_{self} - L_{mutual}$)

Case (2): Inductance of 3-phase Transposed Line with Unsymmetrical Spacing



The effect of complete transposition is to make the line appear as if it was symmetrical. In other words, it makes the characteristics of the line balanced.

$$\therefore L_a = L_b = L_c = 2 \times 10^{-7} \ln \frac{D_{eq}}{r'} \text{ henrys/mt}$$

$$= .7411 \log \frac{D_{eq}}{r'} \text{ mh/mile}$$

where $D_{eq} = \sqrt[3]{D_{12}D_{23}D_{31}}$

$= \text{G.M.D.}$

Case (3): Inductance of Composite-Conductor and Bundled Conductor Lines.

b_1 0, a_1 0, c_1 0, d_1 0 a_2 0, b_2 0, 0 c_2

Single-Phase Line consisting of two composite conductors.

$$I_1 = I_{a_1} + I_{b_1} + I_{c_1} + I_{d_1}$$

$$I_2 = I_{a_2} + I_{b_2} + I_{c_2}$$

and $I_1 + I_2 = 0$

If we assume that the conductors of each group are transposed ~~at~~ AND that the composite groups are also transposed, we can use Geometrical Mean Distances as follows:

Self Geom. Mean Distance of Group 1

$$D_{s_1} = \sqrt[4^2]{(D_{a_1a_1} D_{a_1b_1} D_{a_1c_1} D_{a_1d_1})(D_{b_1a_1} D_{b_1b_1} \cdots)\cdots(D_{d_1a_1} \cdots D_{d_1d_1})}$$

Self Geom. Mean Distance of Group 2

$$D_{s_2} = \sqrt[3^2]{(D_{a_2a_2} D_{a_2b_2} D_{a_2c_2})(D_{b_2a_2} D_{b_2b_2} D_{b_2c_2})(D_{c_2a_2} D_{c_2b_2} D_{c_2c_2})}$$

Mutual Geom. Mean Distance Between Group 1 & Group 2:

$$D_m = \sqrt[4 \times 3]{(D_{a_1a_2} D_{a_1b_2} D_{a_1c_2})(D_{b_1a_2} D_{b_1b_2} D_{b_1c_2})\cdots(D_{d_1a_2} D_{d_1b_2} D_{d_1c_2})}$$

Equiv. Inductance of Group 1:

$$L_1 = 2 \times 10^{-7} \ln \frac{D_m}{D_{s_1}} \text{ henrys/mt}$$

$$= .7411 \log_{10} \frac{D_m}{D_{s_1}} \text{ mh/mile}$$

Equiv. Inductance of Group 2:

$$L_2 = 2 \times 10^{-7} \ln \frac{D_m}{D_{s_2}} \text{ henrys/mt}$$

$$= .7411 \log_{10} \frac{D_m}{D_{s_2}} \text{ mh/mile}$$

and the inductance of the circuit per unit length:

$$L = L_1 + L_2$$

$X_L = 2.022 \times 10^{-3} f \ln \frac{D_m}{D_s}$ Ω/mi

For bundle $D_s = D_s^b$

$D_m = D_{eq}$.

For a two-strand bundle

$$D_s^b = \sqrt[4]{(D_s \times d)^2} = \sqrt{D_s \times d} \tag{3.67}$$

For a three-strand bundle

$$D_s^b = \sqrt[9]{(D_s \times d \times d)^3} = \sqrt[3]{D_s \times d^2} \tag{3.68}$$

For a four-strand bundle

$$D_s^b = \sqrt[16]{(D_s \times d \times d \times d \times 2^{1/2})^4} = 1.09\sqrt[4]{D_s \times d^3} \tag{3.69}$$

In computing inductance using Eq. (3.65), D_s^b of the bundle replaces D_s of a single conductor. To compute D_{eq}, the distance from the center of one bundle to the center of another bundle is sufficiently accurate for D_{ab}, D_{bc}, and D_{ca}. Obtaining the actual GMD between conductors of one bundle and those of another would be almost indistinguishable from the center-to-center distances for the usual spacing.

Example 3.5 Each conductor of the bundled-conductor line shown in Fig. 3.14 is ACSR, 1,272,000-cmil *Pheasant*. Find the inductive reactance in ohms per km (and per mile) per phase for $d = 45$ cm. Also find the per-unit series reactance of the line if its length is 160 km and base is 100 MVA, 345 kV.

SOLUTION From Table A.1 $D_s = 0.0466$ ft, and we multiply feet by 0.3048 to convert to meters.

$$D_s^b = \sqrt{0.0466 \times 0.3048 \times 0.45} = 0.080 \text{ m}$$

$$D_{eq} = \sqrt[3]{8 \times 8 \times 16} = 10.08 \text{ m}$$

$$X_L = 2\pi 60 \times 2 \times 10^{-7} \times 10^3 \ln \frac{10.08}{0.08}$$

$$= 0.365 \ \Omega/\text{km per phase}$$

$$(0.365 \times 1.609 = 0.587 \ \Omega/\text{mi per phase})$$

$$\text{Base } Z = \frac{(345)^2}{100} = 1190 \ \Omega$$

$$X = \frac{0.365 \times 160}{1190} = 0.049 \text{ per unit}$$

For a two-strand bundle $D_s^b = \sqrt[4]{D_{aa} D_{aa'} D_{a'a} D_{a'a'}}$

$D_{aa} = D_s$ from the table

$D_{a'a'} = D_s$ " "

$D_s^b = \sqrt[4]{D_s D_s d d} = \sqrt{D_s \times d}$

$X_L = 2\pi 60 \times 2 \times 10^{-7} \times 10^3 \ln \frac{D_{eq}}{D_s}$ Ω/km

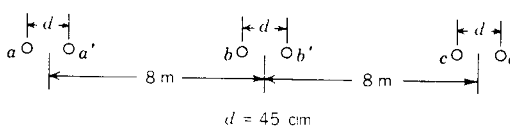


Figure 3.14 Spacing of conductors of a bundled-conductor line.

phase a

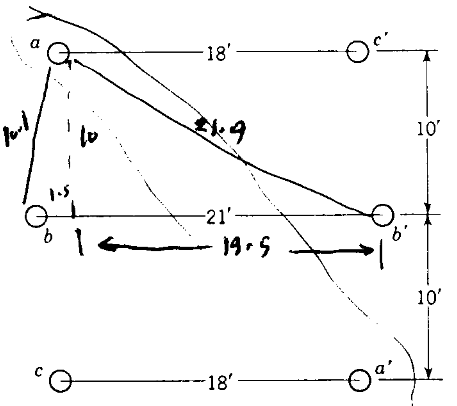


Figure 3.15 Typical arrangement of conductors of a parallel-circuit three-phase line.

$D^p_{bc} = D^p_{ab} = \sqrt[4]{D_{ab} D_{ab'} D_{ba} D_{b'a}} = \sqrt[4]{(D_{ab} D_{ab'})^2}$

$D^p_{ca} = \sqrt[4]{D_{ca} D_{ca'} D_{ac} D_{a'c}} = \sqrt[4]{D_{ca} D_{ca'}}$

$D_{eq} = \sqrt[3]{D^p_{bc} D^p_{ab} D^p_{ca}}$

3.14 PARALLEL-CIRCUIT THREE-PHASE LINES

Two three-phase circuits that are identical in construction and electrically in parallel have the same inductive reactance. The inductive reactance of the single equivalent circuit, however, is half that of each of the individual circuits considered alone only if they are so widely separated that there is negligible mutual inductance between them. If the two circuits are on the same tower, the method of GMD can be used to find the inductance per phase by considering all the conductors of any particular phase to be strands of one composite conductor.

Figure 3.15 shows a typical arrangement of a parallel-circuit three-phase line. Although the line will probably not be transposed, we obtain a practical value for inductance and the calculations are simplified if transposition is assumed. Conductors a and a' are in parallel to compose phase a. Phases b and c are similar. We assume that a and a' take the positions of b and b' and then of c and c' as those conductors are rotated similarly in the transposition cycle.

To calculate D_{eq} the GMD method requires that we use D^p_{ab}, D^p_{bc}, and D^p_{ca}, where the superscript indicates that these quantities are themselves GMD values and where D^p_{ab} means the GMD between the conductors of phase a and those of phase b.

The D_s of Eq. (3.65) is replaced by D^p_s, which is the geometric mean of the GMR values of the two conductors occupying first the positions of a and a', then the positions of b and b', and finally the positions of c and c'. Following each step of Example 3.6 is possibly the best means of understanding the procedure.

Example 3.6 A three-phase double-circuit line is composed of 300,000-cmil 26/7 ACSR *Ostrich* conductors arranged as shown in Fig. 3.15. Find the 60-Hz inductive reactance in ohms per mile per phase.

SOLUTION From Table A.1 for *Ostrich*

$$D_s = 0.0229 \text{ ft}$$

Distance a to b: Original position $= \sqrt{10^2 + 1.5^2} = 10.1$ ft

Distance a to b': Original position $= \sqrt{10^2 + 19.5^2} = 21.9$ ft

The GMDs between phases are

$$D_{ab}^p = D_{bc}^p = \sqrt[4]{(10.1 \times 21.9)^2} = 14.88 \text{ ft}$$

$$D_{ca}^p = \sqrt[4]{(20 \times 18)^2} = 18.97 \text{ ft}$$

$$D_{eq} = \sqrt[3]{14.88 \times 14.88 \times 18.97} = 16.1 \text{ ft}$$

The GMR for the parallel-circuit line is found after first obtaining the GMR values for the three positions. The actual distance from a to a' is $\sqrt{20^2 + 18^2} = 26.9$ ft. Then GMR of each phase is

In position a-a': $\sqrt{26.9 \times 0.0229} = 0.785$ ft

In position b-b': $\sqrt{21 \times 0.0229} = 0.693$ ft

In position c-c': $\sqrt{26.9 \times 0.0229} = 0.785$ ft

Therefore

$$D_s^p = \sqrt[3]{0.785 \times 0.693 \times 0.785} = 0.753 \text{ ft}$$

$$L = 2 \times 10^{-7} \ln \frac{16.1}{0.753} = 6.13 \times 10^{-7} \text{ H/m per phase}$$

$$X_L = 2\pi 60 \times 1609 \times 6.13 \times 10^{-7} = 0.372 \ \Omega/\text{mi per phase}$$

3.15 SUMMARY OF INDUCTANCE CALCULATIONS FOR THREE-PHASE LINES

Although computer programs are usually available or written rather easily for calculating inductance of all kinds of lines, some understanding of the development of the equations used is rewarding from the standpoint of appreciating the effect of variables in designing a line. However, tables like A.1 and A.2 make the calculations quite simple except for parallel-circuit lines. Table A.1 also lists resistance.

The important equation for inductance per phase of single-circuit three-phase lines is given here for convenience

$$L = 2 \times 10^{-7} \ln \frac{D_{eq}}{D_s} \quad \text{H/m per phase} \tag{3.70}$$

Inductive reactance in ohms per kilometer at 60 Hz is found by multiplying inductance in henrys per meter by $2\pi 60 \times 1000$:

$$X_L = 0.0754 \times \ln \frac{D_{eq}}{D_s} \qquad \Omega/\text{km per phase} \tag{3.71}$$

or

$$X_L = 0.1213 \ln \frac{D_{eq}}{D_s} \qquad \Omega/\text{mi per phase} \tag{3.72}$$

Both D_{eq} and D_s must be in the same units, usually feet. If the line has one conductor per phase, D_s is found directly from tables. For bundled conductors D_s^b, as defined in Sec. 3.13, is substituted for D_s. For both single- and bundled-conductor lines

$$D_{eq} = \sqrt[3]{D_{ab} D_{bc} D_{ca}} \tag{3.73}$$

For bundled-conductor lines D_{ab}, D_{bc}, and D_{ca} are distances between the centers of the bundles of phases a, b, and c.

For lines with one conductor per phase it is convenient to determine X_L by adding X_a for the conductor as found in tables like A.1 to X_d as found in Table A.2 corresponding to D_{eq}.

Inductance and inductive reactance of parallel-circuit lines are calculated by following the procedure of Example 3.6.

PROBLEMS

3.1 The all-aluminum conductor identified by the code word *Bluebell* is composed of 37 strands of diameter 0.1672 in. Tables of characteristics of all-aluminum conductors list an area of 1,033,500 cmil for this conductor. Are these values consistent with each other? Find the area in square millimeters.

3.2 Determine the dc resistance in ohms per km of *Bluebell* at 20°C by Eq. (3.2) and the information in Prob. 3.1, and check the result against the value listed in tables of 0.01678 Ω per 1000 ft. Compute the dc resistance in ohms per kilometer at 50°C and compare the result with the ac 60-Hz resistance of 0.1024 Ω/mi listed in tables for this conductor at 50°C. Explain any difference in values.

3.3 An all-aluminum conductor is composed of 37 strands each having a diameter of 0.333 cm. Compute the dc resistance in ohms per kilometer at 75°C.

3.4 A single-phase 60-Hz power line is supported on a horizontal crossarm. Spacing between conductors is 2.5 m. A telephone line is supported on a horizontal crossarm 1.8 m directly below the power line with a spacing of 1.0 m between the centers of its conductors. Find the mutual inductance between the power and telephone circuits and the 60-Hz voltage per kilometer induced in the telephone line if the current in the power line is 150 A.

3.5 If the power and telephone lines described in Prob. 3.4 are in the same horizontal plane and the distance between the nearest conductors of the two lines is 18 m, find the mutual inductance between the circuits and the voltage per mile induced in the telephone line for 150 A in the power line.

3.6 The conductor of a single-phase 60-Hz line is a solid round aluminum wire having a diameter of 0.412 cm. The conductor spacing is 3 m. Determine the inductance of the line in millihenrys per mile. How much of the inductance is due to internal flux linkages? Assume skin effect is negligible.

3.7 Find the GMR of a three-strand conductor in terms of r of an individual strand.