SECTION 4.11

4.34 Considering lines with neutral conductors and earth return, the effect of earth plane is accounted for by the method of _______ with a perfectly conducting earth plane.

4.35 The affect of the earth plane is to slightly increase the capacitance, and as the line height increases, the effect of earth becomes negligible.
(a) True (b) False

SECTION 4.12

4.36 When the electric field strength at a conductor surface exceeds the breakdown strength of air, current discharges occur. This phenomenon is called ______.

4.37 To control corona, transmission lines are usually designed to maintain the calculated conductor surface electric field strength below _______ kV_{rms}/cm.

4.38 Along with limiting corona and its effects, particularly for EHV lines, the maximum ground-level electric field strength needs to be controlled to avoid the shock hazard.
(a) True (b) False

SECTION 4.13

4.39 Considering two parallel three-phase circuits that are close together, when calculating the equivalent series-impedance and shunt-admittance matrices, mutual inductive and capacitive couplings between the two circuits can be neglected.
(a) True (b) False

PROBLEMS

SECTION 4.2

4.1 The *Aluminum Electrical Conductor Handbook* lists a dc resistance of 0.01558 ohm per 1000 ft at 20°C and a 60-Hz resistance of 0.0956 ohm per mile at 50°C for the all-aluminum Marigold conductor, which has 61 strands and whose size is 1113 kcmil. Assuming an increase in resistance of 2% for spiraling, calculate and verify the dc resistance. Then calculate the dc resistance at 50°C, and determine the percentage increase due to skin effect.

4.2 The temperature dependence of resistance is also quantified by the relation $R_2 = R_1[1 + \alpha(T_2 - T_1)]$ where R_1 and R_2 are the resistances at temperatures T_1 and T_2, respectively, and α is known as the temperature coefficient of resistance. If a copper wire has a resistance of 55 Ω at 20°C, find the maximum permissible operating temperature of the wire if its resistance is to increase by at most 20%. Take the temperature coefficient at 20°C to be $\alpha = 0.00382$.

4.3 A transmission-line cable with a length of 2 km consists of 19 strands of identical copper conductors, each 1.5 mm in diameter. Because of the twist of the strands, the actual length of each conductor is increased by 5%. Determine the resistance of the cable if the resistivity of copper is 1.72 $\mu\Omega$-cm at 20°C.

4.4 One thousand circular mils or 1 kcmil is sometimes designated by the abbreviation MCM. Data for commercial bare-aluminum electrical conductors lists a 60 Hz resistance of 0.0080 ohm per kilometer at 75°C for a 793-MCM AAC conductor.

(a) Determine the cross-sectional conducting area of this conductor in square meters.

(b) Find the 60 Hz resistance of this conductor in ohms per kilometer at 50°C.

4.5 A 60-Hz, 765-kV, three-phase overhead transmission line has four ACSR 900 kcmil 54/3 conductors per phase. Determine the 60 Hz resistance of this line in ohms per kilometer per phase at 50°C.

4.6 A three-phase overhead transmission line is designed to deliver 190.5 MVA at 220 kV over a distance of 63 km, such that the total transmission line loss is not to exceed 2.5% of the rated line MVA. Given the resistivity of the conductor material to be 2.84×10^{-8} Ω-m, determine the required conductor diameter and the conductor size in circular mils. Neglect power losses due to insulator leakage currents and corona.

4.7 If the per-phase line loss in a 70-km-long transmission line is not to exceed 65 kW while it is delivering 100 A per phase, compute the required conductor diameter if the resistivity of the conductor material is 1.72×10^{-8} Ω-m.

SECTIONS 4.4 AND 4.5

4.8 A 60-Hz, single-phase two-wire overhead line has solid cylindrical copper conductors with a 1.5 cm diameter. The conductors are arranged in a horizontal configuration with 0.5 m spacing. Calculate in mH/km (a) the inductance of each conductor due to internal flux linkages only, (b) the inductance of each conductor due to both internal and external flux linkages, and (c) the total inductance of the line.

4.9 Rework Problem 4.8 if the diameter of each conductor is (a) increased by 20% to 1.8 cm or (b) decreased by 20% to 1.2 cm without changing the phase spacing. Compare the results with those of Problem 4.8.

4.10 A 60-Hz, three-phase three-wire overhead line has solid cylindrical conductors arranged in the form of an equilateral triangle with 4-ft conductor spacing. The conductor diameter is 0.5 in. Calculate the positive-sequence inductance in H/m and the positive-sequence inductive reactance in Ω/km.

4.11 Rework Problem 4.10 if the phase spacing is (a) increased by 20% to 4.8 ft or (b) decreased by 20% to 3.2 ft. Compare the results with those of Problem 4.10.

4.12 Find the inductive reactance per mile of a single-phase overhead transmission line operating at 60 Hz given the conductors to be *Partridge* and the spacing between centers to be 30 ft.

4.13 A single-phase overhead transmission line consists of two solid aluminum conductors having a radius of 3 cm with a spacing 3.5 m between centers. (a) Determine the total line inductance in mH/m. (b) Given the operating frequency to be 60 Hz, find the total inductive reactance of the line in Ω/km and in Ω/mi. (c) If the spacing is doubled to 7 m, how does the reactance change?

4.14 (a) In practice, one deals with the inductive reactance of the line per phase per mile and use the logarithm to the base 10. Show that Eq. (4.5.9) of the text can be rewritten as

$x = k \log \frac{D}{r'}$ ohms per mile per phase

$= x_d + x_a$

where $x_d = k \log D$ is the inductive reactance spacing factor in ohms per mile

$x_a = k \log \frac{1}{r'}$ is the inductive reactance at 1-ft spacing in ohms per mile

$k = 4.657 \times 10^{-3} f = 0.2794$ at 60 Hz

(b) Determine the inductive reactance per mile per phase at 60 Hz for a single-phase line with phase separation of 10 ft and conductor radius of 0.06677 ft. If the spacing is doubled, how does the reactance change?

SECTION 4.6

4.15 Find the GMR of a stranded conductor consisting of six outer strands surrounding and touching one central strand, all strands having the same radius r.

4.16 A bundle configuration for UHV lines (above 1000 kV) has identical conductors equally spaced around a circle, as shown in Figure 4.29. N_b is the number of conductors in the bundle, A is the circle radius, and D_S is the conductor GMR. Using the distance D_{1n} between conductors 1 and n given by $D_{1n} = 2A \sin[(n-1)\pi/N_b]$ for $n = 1, 2, \ldots, N_b$, and the following trigonometric identity:

$$[2\sin(\pi/N_b)][2\sin(2\pi/N_b)][2\sin(3\pi/N_b)]\cdots[2\sin\{(N_b-1)\pi/N_b\}] = N_b$$

show that the bundle GMR, denoted D_{SL}, is

$$D_{SL} = [N_b D_S A^{(N_b-1)}]^{(1/N_b)}$$

Also show that the above formula agrees with (4.6.19) through (4.6.21) for EHV lines with $N_b = 2, 3$, and 4.

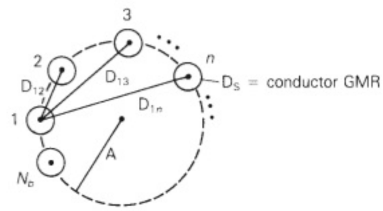


FIGURE 4.29
Bundle configuration for Problem 4.16

4.17 Determine the GMR of each of the unconventional stranded conductors shown in Figure 4.30. All strands have the same radius *r*.

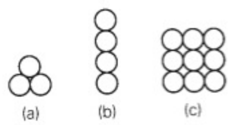


FIGURE 4.30
Unconventional stranded conductors for Problem 4.17

4.18 A 230-kV, 60-Hz, three-phase completely transposed overhead line has one ACSR 954 kcmil conductor per phase and flat horizontal phase spacing, with 7 m between adjacent conductors. Determine the inductance in H/m and the inductive reactance in Ω/km.

4.19 Rework Problem 4.18 if the phase spacing between adjacent conductors is (a) increased by 10% to 7.7 m or (b) decreased by 10% to 6.3 m. Compare the results with those of Problem 4.18.

4.20 Calculate the inductive reactance in Ω/km of a bundled 500-kV, 60-Hz, three-phase completely transposed overhead line having three ACSR 1113 kcmil conductors per bundle, with 0.5 m between conductors in the bundle. The horizontal phase spacings between bundle centers are 10, 10, and 20 m.

4.21 Rework Problem 4.20 if the bundled line has (a) three ACSR, 1351 kcmil conductors per phase or (b) three ACSR, 900 kcmil conductors per phase, without changing the bundle spacing or the phase spacings between bundle centers. Compare the results with those of Problem 4.20.

4.22 The conductor configuration of a bundled single-phase overhead transmission line is shown in Figure 4.31. Line X has its three conductors situated at the corners of an equilateral triangle with 10 cm spacing. Line Y has its three conductors arranged in a horizontal configuration with 10 cm spacing. All conductors are identical, solid-cylindrical conductors each with a radius of 2 cm. Find the equivalent representation in terms of the geometric mean radius of each bundle and a separation that is the geometric mean distance.

FIGURE 4.31
Problem 4.22

4.23 Figure 4.32 shows the conductor configuration of a completely transposed three-phase overhead transmission line with bundled phase conductors. All conductors have a radius of 0.74 cm with a 30-cm bundle spacing. (a) Determine the inductance per phase in mH/km and in mH/mi. (b) Find the inductive line reactance per phase in Ω/mi at 60 Hz.

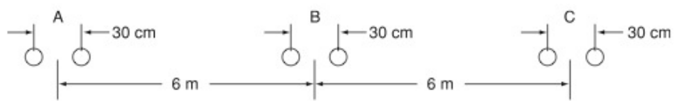


FIGURE 4.32
Problem 4.23

4.24 Consider a three-phase overhead line made up of three phase conductors: Linnet, 336.4 kcmil, and ACSR 26/7. The line configuration is such that the horizontal separation between center of C and that of A is 40", and between that of A and B is also 40" in the same line; the vertical separation of A from the line of C–B is 16". If the line is operated at 60 Hz at a conductor temperature of 75°C, determine the inductive reactance per phase in Ω/mi,
(a) by using the formula given in Problem 4.14 (a), and
(b) by using (4.6.18) from the text.

4.25 For the overhead line of configuration shown in Figure 4.33 operating at 60 Hz and a conductor temperature of 70°C, determine the resistance per phase, inductive reactance in ohms/mile/phase, and the current-carrying capacity of the overhead line. Each conductor is ACSR Cardinal of Table A.4.

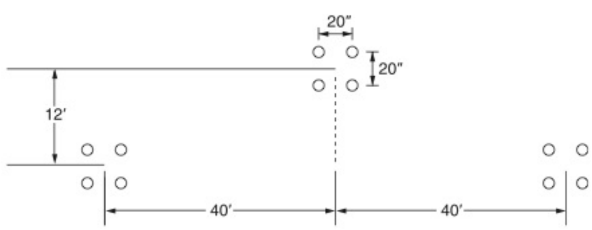


FIGURE 4.33
Line configuration for Problem 4.25

4.26 Consider a symmetrical bundle with N subconductors arranged in a circle of radius A. The inductance of a single-phase symmetrical bundle-conductor line is given by

$$L = 2 \times 10^{-7} \ln \frac{GMD}{GMR} \text{ H/m}$$

Where GMR is given by $[Nr'(A)^{N-1}]^{1/N}$ $r' = (e^{-1/4} r)$, r being the subconductor radius, and GMD is approximately the distance D between the bundle centers. Note that A is related to the subconductor spacing S in the bundle circle by $S = 2A \sin(\Pi/N)$

Now consider a 965-kV, single-phase, bundle-conductor line with eight subconductors per phase, phase spacing D = 20 m, and the subconductor spacing S = 45.72 cm. Each subconductor has a diameter of 4.572 cm. Determine the line inductance in H/m.

4.27 Figure 4.34 shows double-circuit conductors' relative positions in segment 1 of transposition of a completely transposed three-phase overhead transmission line. The inductance is given by

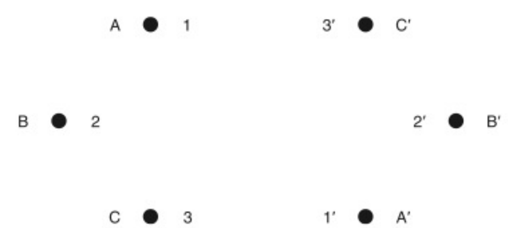
$$L = 2 \times 10^{-7} \ln \frac{GMD}{GMR} \text{ H/m/phase}$$

Where $GMD = (D_{AB_{eq}} D_{BC_{eq}} D_{AC_{eq}})^{1/3}$

With mean distances defined by equivalent spacings

FIGURE 4.34

For Problem 4.27 (Double-circuit conductor configuration)



$$D_{AB_{eq}} = (D_{12} D_{1'2'} D_{12'} D_{1'2})^{1/4}$$

$$D_{BC_{eq}} = (D_{23} D_{2'3'} D_{2'3} D_{23'})^{1/4}$$

$$D_{AC_{eq}} = (D_{13} D_{1'3'} D_{13'} D_{1'3})^{1/4}$$

And $GMR = [(GMR)_A (GMR)_B (GMR)_C]^{1/3}$ with phase GMRs defined by

$$(GMR)_A = [r' D_{11'}]^{1/2}; \quad (GMR)_B = [r' D_{22'}]^{1/2}; \quad (GMR)_C = [r' D_{33'}]^{1/2}$$

and r' is the GMR of phase conductors.

Now consider a 345-kV, three-phase, double-circuit line with phase-conductor's GMR of 0.0588 ft and the horizontal conductor configuration shown in Figure 4.35.

Find the relative error involved

FIGURE 4.35 For Problem 4.27

(a) Determine the inductance per meter per phase in Henries (H).
(b) Calculate the inductance of just one circuit and then divide by 2 to obtain the inductance of the double circuit.

4.28 For the case of double-circuit, bundle-conductor lines, the same method indicated in Problem 4.27 applies with r' replaced by the bundle's GMR in the calculation of the overall GMR.

Now consider a double-circuit configuration shown in Figure 4.36 that belongs to a 500-kV, three-phase line with bundle conductors of three subconductors at 21 in. spacing. The GMR of each subconductor is given to be 0.0485 ft.

Determine the inductive reactance of the line in ohms per mile per phase. You may use

$$X_L = 0.2794 \log \frac{GMD}{GMR} \ \Omega/\text{mi/phase}$$

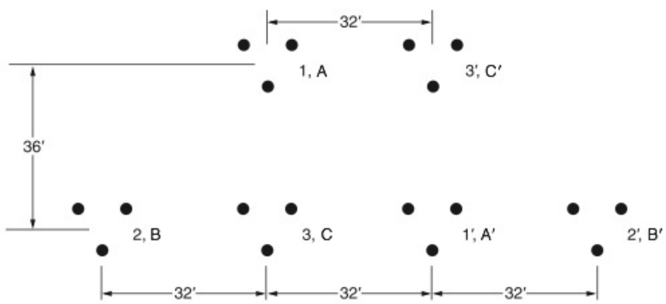


FIGURE 4.36 Configuration for Problem 4.28

4.29 Reconsider Problem 4.28 with an alternate phase placement given below:

	Physical Position					
	1	2	3	1′	2′	3′
Phase Placement	A	B	B′	C	C′	A′

Calculate the inductive reactance of the line in Ω/mi/phase.

4.30 Reconsider Problem 4.28 with still another alternate phase placement shown below.

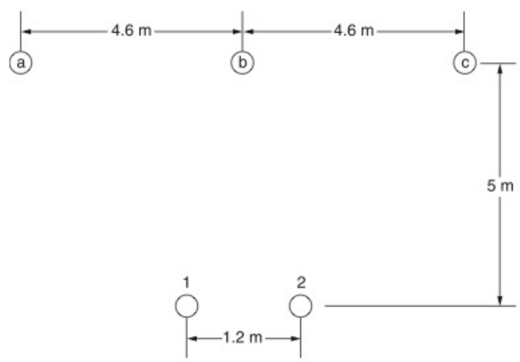
	Physical Position					
	1	2	3	1′	2′	3′
Phase Placement	C	A	B	B	A	C

Find the inductive reactance of the line in Ω/mi/phase.

4.31 Figure 4.37 shows the conductor configuration of a three-phase transmission line and a telephone line supported on the same towers. The power line carries a balanced current of 250 A/phase at 60 Hz, while the telephone line is directly located below phase b. Assume balanced three-phase currents in the power line. Calculate the voltage per kilometer induced in the telephone line.

FIGURE 4.37

Conductor layout for Problem 4.31



SECTION 4.9

4.32 Calculate the capacitance-to-neutral in F/m and the admittance-to-neutral in S/km for the single-phase line in Problem 4.8. Neglect the effect of the earth plane.

4.33 Rework Problem 4.32 if the diameter of each conductor is (a) increased by 20% to 1.8 cm or (b) decreased by 20% to 1.2 cm. Compare the results with those of Problem 4.32.

4.34 Calculate the capacitance-to-neutral in F/m and the admittance-to-neutral in S/km for the three-phase line in Problem 4.10. Neglect the effect of the earth plane.

4.35 Rework Problem 4.34 if the phase spacing is (a) increased by 20% to 4.8 ft or (b) decreased by 20% to 3.2 ft. Compare the results with those of Problem 4.34.

4.36 The line of Problem 4.23 as shown in Figure 4.32 is operating at 60 Hz. Determine (a) the line-to-neutral capacitance in nF/km per phase and in nF/mi per phase; (b) the capacitive reactance in Ω-km per phase and in Ω-mi per phase; and (c) the capacitive reactance in Ω per phase for a line length of 100 mi.

4.37 (a) In practice, one deals with the capacitive reactance of the line in ohms · mi to neutral. Show that Eq. (4.9.15) of the text can be rewritten as

$$X_C = k' \log \frac{D}{r} \quad \text{ohms} \cdot \text{mi to netural}$$
$$= x'_d + x'_a$$

where $x'_d = k' \log D$ is the capacitive reactance spacing factor
$x'_a = k' \log \frac{1}{r}$ is the capacitive reactance at 1-ft spacing
$k' = (4.1 \times 10^6)/f = 0.06833 \times 10^6$ at $f = 60$ Hz

(b) Determine the capacitive reactance in Ω · mi. for a single-phase line of Problem 4.14. If the spacing is doubled, how does the reactance change?

4.38 The capacitance per phase of a balanced three-phase overhead line is given by

$$C = \frac{0.0389}{\log(\text{GMD}/r)} \mu f/\text{mi/phase}$$

For the line of Problem 4.24, determine the capacitive reactance per phase in Ω · mi.

SECTION 4.10

4.39 Calculate the capacitance-to-neutral in F/m and the admittance-to-neutral in S/km for the three-phase line in Problem 4.18. Also calculate the line-charging current in kA/phase if the line is 110 km in length and is operated at 230 kV. Neglect the effect of the earth plane.

4.40 Rework Problem 4.39 if the phase spacing between adjacent conductors is (a) increased by 10% to 7.7 m or (b) decreased by 10% to 6.3 m. Compare the results with those of Problem 4.39.

4.41 Calculate the capacitance-to-neutral in F/m and the admittance-to-neutral in S/km for the line in Problem 4.20. Also calculate the total reactive power in Mvar/km supplied by the line capacitance when it is operated at 500 kV. Neglect the effect of the earth plane.

4.42 Rework Problem 4.41 if the bundled line has (a) three ACSR, 1351-kcmil conductors per phase or (b) three ACSR, 900 kcmil conductors per phase without changing the bundle spacing or the phase spacings between bundle centers.

4.43 Three ACSR *Drake* conductors are used for a three-phase overhead transmission line operating at 60 Hz. The conductor configuration is in the form of an isosceles triangle with sides of 20, 20, and 38 ft. (a) Find the capacitance-to-neutral and capacitive reactance-to-neutral for each 1-mile length of line. (b) For a line length of 175 mi and a normal operating voltage of 220 kV, determine the capacitive reactance-to-neutral for the entire line length as well as the charging current per mile and total three-phase reactive power supplied by the line capacitance.

4.44 Consider the line of Problem 4.25. Calculate the capacitive reactance per phase in $\Omega \cdot$ mi.

SECTION 4.11

4.45 For an average line height of 10 m, determine the effect of the earth on capacitance for the single-phase line in Problem 4.32. Assume a perfectly conducting earth plane.

4.46 A three-phase 60-Hz, 125-km overhead transmission line has flat horizontal spacing with three identical conductors. The conductors have an outside diameter of 3.28 cm with 12 m between adjacent conductors. (a) Determine the capacitive reactance-to-neutral in Ω-m per phase and the capacitive reactance of the line in Ω per phase. Neglect the effect of the earth plane. (b) Assuming that the conductors are horizontally placed 20 m above ground, repeat part (a) while taking into account the effect of ground. Consider the earth plane to be a perfect conductor.

4.47 For the single-phase line of Problem 4.14 (b), if the height of the conductor above ground is 80 ft., determine the line-to-line capacitance in F/m. Neglecting earth effect, evaluate the relative error involved. If the phase separation is doubled, repeat the calculations.

4.48 The capacitance of a single-circuit, three-phase transposed line with the configuration shown in Figure 4.38, including ground effect, and with conductors not equilaterally spaced is given by

$$C_{an} \frac{2\pi\varepsilon_0}{\ln \frac{D_{eq}}{r} - \ln \frac{H_m}{H_s}} \text{ F/m line-to-neutral}$$

where $D_{eq} = \sqrt[3]{D_{12}D_{23}D_{13}} = \text{GMD}$

r = conductor's outside radius

$$H_m = (H_{12}H_{23}H_{13})^{1/3}$$

$$H_s = (H_1H_2H_3)^{1/3}$$