Power System Analysis
供電=用電

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3.0簡介(Introduction)

A line is characterized by four distributed parameters: series resistance, series inductance, shunt conductance, and shunt capacitance (assuming without mutual inductance and capacitance).

Resistance: $R=\rho(l/A)$, ρ (resistivity:電阻率Ωm), length: l, cross-sectional area: A. (Conductor, Semiconductor, and Insulator)

Silver: $\rho = 1.64\text{x}10^{-8}$ Ωm,

Copper: $\rho = 1.72\text{x}10^{-8}$ Ωm, $R=1.72\text{x}10^{-8}$ x1km/ $\pi(0.01\text{m})^2$ =0.0547Ω

Aluminum: $\rho = 2.8\text{x}10^{-8}$ Ωm,

Gold: $\rho = 2.45\text{x}10^{-8}$ Ωm,

Carbon: $\rho = 4\text{x}10^{-5}$ Ωm, Germanium (鍺): $\rho = 4.7\text{x}10^{-1}$ Ωm, Silicon: $\rho = 6.4\text{x}10^{2}$ Ωm,

Paper: $\rho = 10^{10}$ Ωm, Mica (雲母): $\rho = 5\text{x}10^{11}$ Ωm, Glass: $\rho = 10^{12}$ Ωm, Teflon: $\rho = 3\text{x}10^{12}$ Ωm, Air: $\rho = 1.5\text{x}10^{14}$ Ωm,

集膚效應(Skin Effect)

In high frequency applications the current in a good conductor tends to shift to the surface of the conductor (due to the skin effect).

Resistance: $R=\rho(l/A)$, ρ (resistivity:電阻率Ωm), $\sigma = 1/\rho$ (conductivity: 導電率1/Ωm =A/(V × m))

Skin Depth,$\delta = 1/(\pi f \mu \sigma)^{0.5}$, $\mu_o = 4\pi \times 10^{-7}$ (H/m)(permeability:導磁係數)

Silver: $\sigma = 6.17\text{x}10^7$, δ =8.27mm (at 60Hz), δ =0.064mm (at 1MHz)

Copper: $\sigma = 5.8\text{x}10^7$, δ =8.53mm (at 60Hz), δ =0.066mm (at 1MHz)

Aluminum: $\sigma = 3.54\text{x}10^7$,δ =10.92mm (at 60Hz), δ =0.084mm (at 1MHz)

Gold: $\sigma = 4.1\text{x}10^7$, δ =10.14mm (at 60Hz), δ =0.079mm (at 1MHz)

Iron($\mu_r = 10^3$): σ=100x10^7 , δ=0.65mm (at 60Hz), δ =0.005mm (at 1MHz)

Seawater : $\sigma = 4$, δ =32m (at 60Hz), δ =0.25m (at 1MHz)

$\varepsilon_o = (1/36\pi) \times 10^{-9}$ (F/m)(permittivity:介電係數)

Speed of light: $C=1/(\mu_o\, \varepsilon_o)^{0.5} = 3\text{x}10^8$ m/s, [(H・F)=(s^2),亨利・法拉= s^2]

Wave length of 60Hz: $\lambda = C/f = 5\text{x}10^6$ m.

3.1磁學回顧(Review of Magnetics)

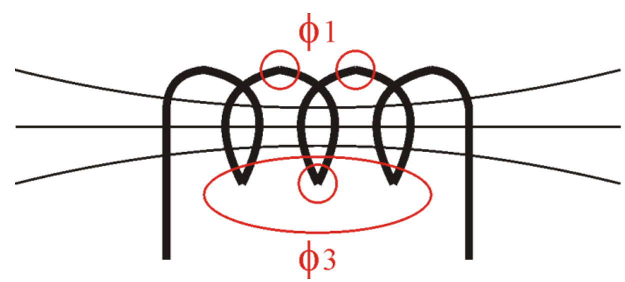
Ampere's Circuital Law: $F = \oint \mathrm{H} \cdot \mathrm{d}l = \mathrm{N}i$ (3.1)

(3.2) $\mathrm{H} \cdot \mathrm{d}l = \mathrm{H}\mathrm{d}l \cos\theta$, (3.3)$\mathrm{B} = \mu \mathrm{H}$, $\mathrm{B} = \Phi/\mathrm{A}$, μ (permeability)

(3.4) $\Phi = \int_A \mathrm{B} \cdot \mathrm{da}$, (3.5) $\Phi = \mathrm{BA}$, Φ: flux, B: flux density (webers/m^2), H: magnetic field intensity (A・turn/m)

磁通鏈Flux linkages: (3.6) $\lambda = \mathrm{N}\Phi = \mathrm{L}i = \sum_{i=1}^{N} \Phi_i$ (3.7)

電感inductance : (3.8) $\lambda = \mathrm{L}i$,



Ex3.1 Calculate the inductance.

$F = \underline{\mathrm{H}l = \mathrm{N}i}$

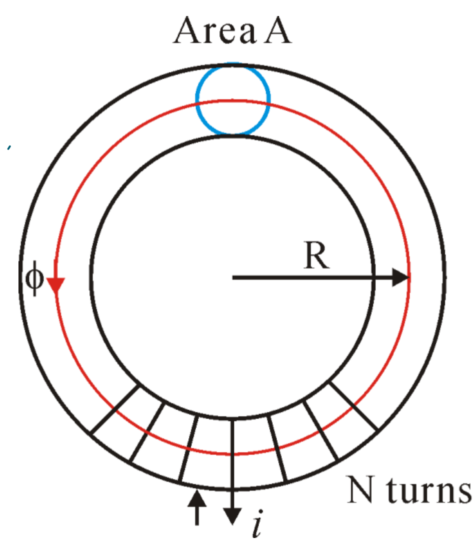
$\mathrm{B} = \mu \mathrm{H} = \mu \mathrm{N}i/l$, $\rightsquigarrow i = \frac{\mathrm{B}l}{\mu \mathrm{N}}$

$\Phi = \mathrm{BA} = (\mu \mathrm{A}/l)\mathrm{N}i$,

→ 電感∝圈數平方.

$L = \lambda/i = \mathrm{N}\underbrace{\Phi}_{\mathrm{BA}}/\underbrace{i}_{\frac{\mathrm{B}l}{\mu \mathrm{N}}} = \frac{\mathrm{NBA}}{\frac{\mathrm{B}l}{\mu \mathrm{N}}} = \frac{\mu \mathrm{N}^2 \mathrm{A}}{l} = (\mu \mathrm{AN}^2/l) = \mu \mathrm{AN}^2/(2\pi \mathrm{R})$

inductance: relates flux linkage to current



3.2無限長直電線的磁通鏈
(Flux Linkages of Infinite Straight Wire)

Figure 3.2: wire carrying current (N=1)

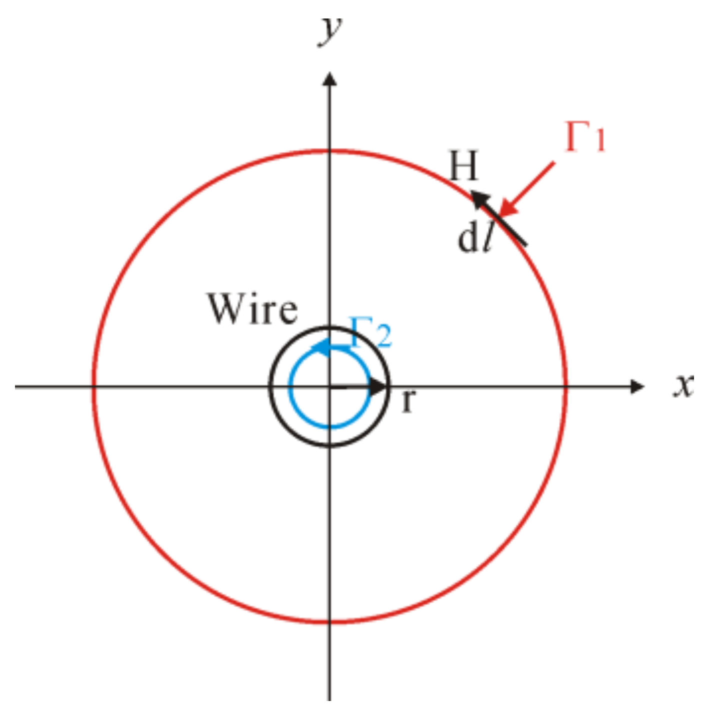
Case 1 (x > r): $F = \oint H \cdot dl = i = H \cdot 2\pi x \Rightarrow H = i/(2\pi x)$ (3.9a)

Case 2 (x ≦ r): $\boxed{\oint H \cdot dl = i_e} \Rightarrow \boxed{\underbrace{(\pi x^2/\pi r^2) i}_{\text{電流,}} = H \cdot 2\pi x}$

=> (3.9b) $H = (x/2\pi r^2) i$

(3.10) $B = \mu_r \mu_o H$, $\mu_o = 4\pi \times 10^{-7}$,

μ_r of the air, copper, and aluminum is near 1.



3.2無限長直電線的磁通鏈(Flux Linkages of Infinite Straight Wire)

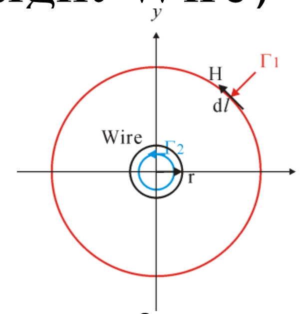


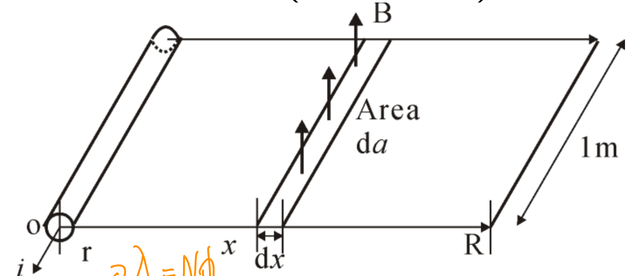
Figure 3.2: wire carrying current (N=1)

Case 1 (x > r): $F = \oint H \cdot dl = i = H \cdot 2\pi x \Rightarrow H = i/(2\pi x)$

Case 2 (x ≦ r): $\oint H \cdot dl = i_e = (\pi x^2/ \pi r^2)i = H \cdot 2\pi x \Rightarrow H = (x/ 2\pi r^2)i$

$B = \mu_r \mu_o H$, $\mu_o = 4\pi \times 10^{-7}$,

μ_r of the air, copper, and aluminum is near 1.



→λ=Nϕ

Figure 3.3: infinite wire of radius r, find flux crossing rectangle (N=1).

→μ₀H(x)

Case 1 (x >r, N=1): $\lambda_1 = \Phi_1 = \int_A B(x)dx = \mu_o \int_A H(x)dx = \mu_o \int_r^R i/(2\pi x)\, dx$

$= (\mu_o\, i/2\pi)\ln(R/r)$. (Caution: R-> ∞)

Case 2 (x≦r, N=πx²/πr²): $\lambda_2 = \mu_r \mu_o \int_0^r (x/2\pi r^2)(\pi x^2/\pi r^2)i\, dx = \mu_r \mu_o\, i/(8\pi)$

Total Flux Linkages per meter of one Infinite Straight Wire :

$\lambda = \lambda_2 + \lambda_1 = (\mu_o\, i/2\pi)[\mu_r/4 + \ln(R/r)]$

3.3 多導體情況下的磁通鏈(Flux Linkages of Multi-Conductors)

Total Flux Linkages per meter of one Infinite Straight Wire :

(上頁的)

$\lambda=\lambda_2+\lambda_1=(\mu_o\, i/2\pi)[\mu_r/4+\ln(R/r)]$

Total Flux Linkages per meter of multi-Conductors for wire 1:

$$\lambda_1=(\mu_o/2\pi)\{i_1[\mu_r/4+\ln(R_1/r_1)]+i_2\ln(R_2/d_{12})+\cdot\ \cdot+i_n\ln(R_n/d_{1n})\}$$

$$=(\mu_o/2\pi)\{i_1[\mu_r/4+\ln(1/r_1)]+i_2\ln(1/d_{12})+\cdot\ \cdot+i_n\ln(1/d_{1n})\}$$

$$+(\mu_o/2\pi)\boxed{[i_1(\ln(R_1)+i_2\ln(R_2)+\cdot\ \cdot+i_n\ln(R_n)]}=0.$$

Assuming $\boxed{i_1+i_2+\cdot\ \cdot+i_n=0}$ and $R_1=R_2=\cdot\ \cdot=R_n=R$

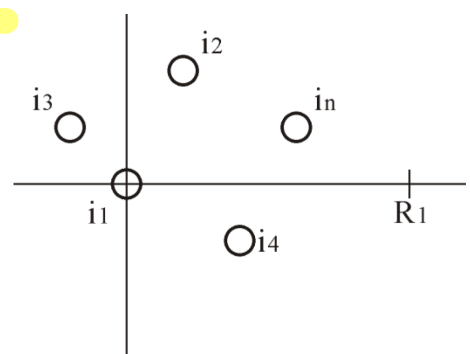
$$\lambda_1=(\mu_o/2\pi)\{i_1[\mu_r/4+\ln(1/r_1)]+i_2\ln(1/d_{12})+\cdot\ \cdot+i_n\ln(1/d_{1n})\}$$

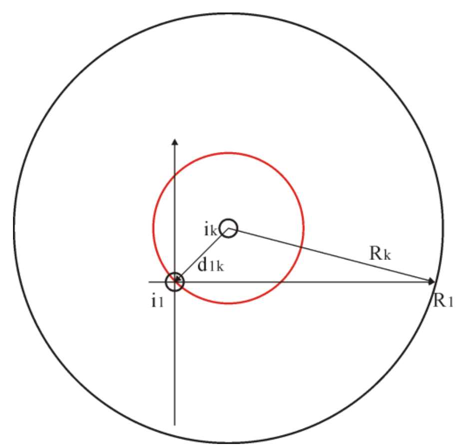
$$=l_{11}i_1+l_{12}i_2+\cdot\ \cdot+l_{1n}i_n$$

$$\lambda_k=(\mu_o/2\pi)\{i_1(\ln(1/d_{k1})+i_2\ln(1/d_{k2})+\cdot+i_k[\mu_r/4+(\ln(1/r_k)]+\cdot+i_n\ln(1/d_{kn})]\}$$

$$=l_{k1}i_1+l_{k2}i_2+\cdot+l_{kk}i_k+\cdot+l_{kn}i_n$$

$$\overbrace{\boxed{\frac{\mu_0}{2\pi}\cdot\ln\left(\frac{1}{d_{12}}\right)}}^{l_{12}}\cdot i_2.$$



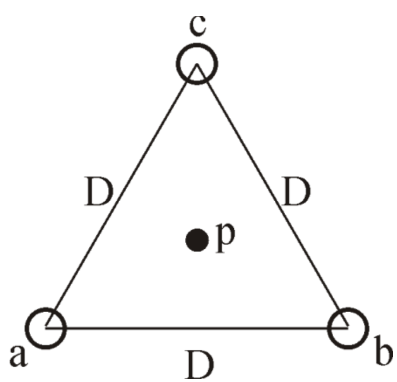


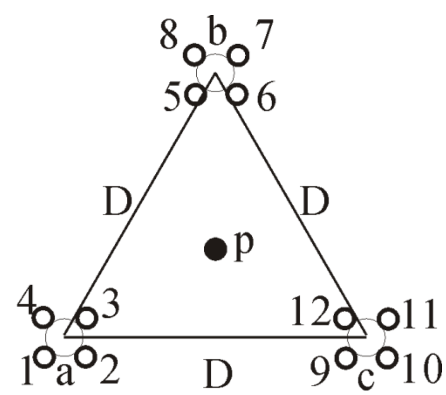
Ex3.2 Calculate the inductance per meter of each phase of a three-phase transmission line.

Assume that 1. Conductors equally spaced D and have equal radii r.

2. $i_a + i_b + i_c = 0$.

$$\lambda_a = (\mu_o/2\pi)\{i_a[\mu_r/4 + \ln(1/r)] + i_b \ln(1/D) + i_c \ln(1/D)\}$$
$$= (\mu_o/2\pi)\{i_a[\mu_r/4 + \ln(1/r)] - i_a \ln(1/D)\}$$
$$= (\mu_o/2\pi)[\mu_r/4 + \ln(1/r) - \ln(1/D)] \times i_a$$
$$= (\mu_o/2\pi)[\ln e^{(\mu r/4)} + \ln(1/r) - \ln(1/D)] \times i_a$$
$$= (\mu_o/2\pi)[\ln(1/r\, e^{-(\mu r/4)}) - \ln(1/D)] \times i_a$$
$$= (\mu_o/2\pi)[\ln(1/r') - \ln(1/D)] \times i_a$$
$$= (\mu_o/2\pi)[\ln(D/r')] \times i_a$$
$$= l_a \times i_a$$





Assume that 1. D = 1m, r = 0.01m.

$\mu_r = 1$, $\mu_o = 4\pi \times 10^{-7}$,

$l_a = ?$

3.4捆束導體(Conductor Bundling)

$\lambda_1 = (\mu_o/2\pi)\{ (i_a/4)[\mu_r/4 + \ln(1/r) + \ln(1/d_{12}) + \ln(1/d_{13}) + \ln(1/d_{14})]$

$\qquad + (i_b/4)[\ln(1/d_{15}) + \ln(1/d_{16}) + \ln(1/d_{17}) + \ln(1/d_{18})]$

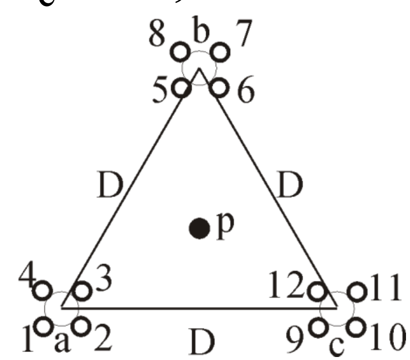
$\qquad + (i_c/4)[\ln(1/d_{19}) + \ln(1/d_{1,10}) + \ln(1/d_{1,11}) + \ln(1/d_{1,12})] \}$

$\quad = (\mu_o/2\pi)(i_a \ln 1/R_{GMR} + i_b \ln 1/D_{1b} + i_c \ln 1/D_{1c}$

$r' = r\, e^{-(\mu r/4)}$, $R_{GMR} = (r' d_{12} d_{13} d_{14})^{1/4}$ (geometric mean radius)

$D_{1b} = (d_{15} d_{16} d_{17} d_{18})^{1/4}$, $D_{1c} = (d_{19} d_{1,10} d_{1,11} d_{1,12})^{1/4}$

Assuming $D_{1b} = D_{1c} = D$ (geometric mean distance), $i_a + i_b + i_c = 0$,



$\lambda_1 = (\mu_o/2\pi)\, i_a \ln D/R_{GMR}$

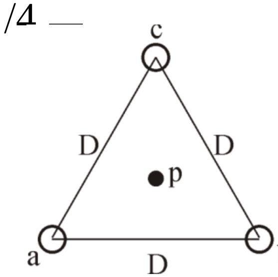
Inductance $l_1 = \lambda_1/(i_a/4) = 4\,(\mu_o/2\pi) \ln D/R_{GMR}$

For phase a: $l_1 = l_2 = l_3 = l_4$, and four parallel lines,

$l_a = l_1/4 = (\mu_o/2\pi) \ln D/R_{GMR}$, and $l_a = l_b = l_c$

Ex3.3 Find the geometric mean radius (GMR) of three symmetrically spaced conductors. Assume that r = 2cm and $r' = r\, e^{-(\mu r/4)} = 2e^{-1/4}$ — 1.56 cm ,

$d_{12} = d_{13} = d_{23} = 50\text{cm}$, $R_{GMR} = (r' d_{12} d_{13})^{1/3} = ?$,



3.5移位(Transposition)

It is usually more convenient to arrange the phases in a horizontal or vertical configuration, therefore the symmetry is lost. One way to regain the symmetry and restore balanced conditions is to use the method of transposition of lines.

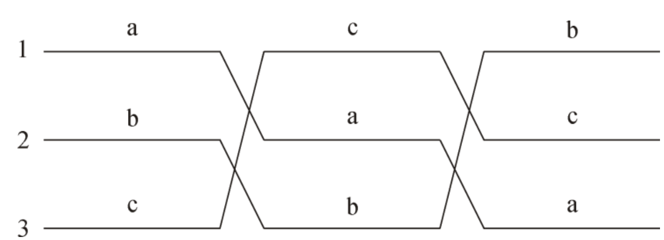
$\lambda_a\backslash = (\lambda_{a1} + \lambda_{a2} + \lambda_{a3})/3$, $D_m = (d_{12}\, d_{23}\, d_{13})^{1/3}$,

$$\lambda_a\backslash = (1/3)(\mu_o/2\pi)\{\, i_a \ln(1/r') + i_b \ln(1/d_{12}) + i_c \ln(1/d_{13})$$
$$+ i_a \ln(1/r') + i_b \ln(1/d_{23}) + i_c \ln(1/d_{12})$$
$$+ i_a \ln(1/r') + i_b \ln(1/d_{13}) + i_c \ln(1/d_{23}) \,\}$$

$$\lambda_a\backslash = (\mu_o/2\pi)\{\, i_a \ln(1/r') + i_b \ln(1/D_m) + i_c \ln(1/D_m) \,\}$$
$$= (\mu_o/2\pi)\{\, i_a \ln(1/r') - i_a \ln(1/D_m) \,\} = (\mu_o/2\pi)\, i_a \ln(D_m/r')$$

$l_a\backslash = l_b\backslash = l_c\backslash = (\mu_o/2\pi)\ln(D_m/r')$ for one line transposition

$l_a\backslash = l_b\backslash = l_c\backslash = (\mu_o/2\pi)\ln(D_m/R_{GMR})$ for conductor bundling transposition



Ex 3.5 Find the inductance per meter of the 3-phase line shown in figure E3.5. The conductors are aluminum ($\mu_r = 1$), with radius r = 0.5 inch, $d_{12} = d_{23} = 20$ ft, $d_{13} = 40$ ft, each phase has two conductors and distance is 18 inch.

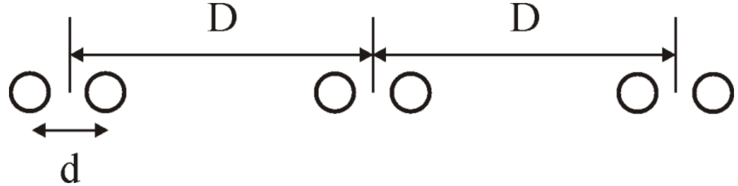
(a) $r' = r\, e^{-(\mu r/4)} = 0.5 \times 0.78$, $R_{GMR} = (r' \times 18)^{1/2} = 2.65 \text{ inch} = 0.22 \text{ ft}$

(b) $Dm = (\overset{d_{12}}{20} \text{ ft} \times \overset{d_{23}}{20} \text{ ft} \times \overset{d_{13}}{40} \text{ ft})^{1/3} = 25.2 \text{ ft}$

(c) $l_a \backslash = l_b \backslash = l_c \backslash = (\mu_o / 2\pi) \ln(D_m / R_{GMR}) = 2 \times 10^{-7} \ln(25.2/0.22)$

$= 9.47 \times 10^{-7}$ H/m

$e^{-(\frac{1}{4})} = e^{-0.25} = 0.78$



3.6電場回顧(Review of Electric Fields)

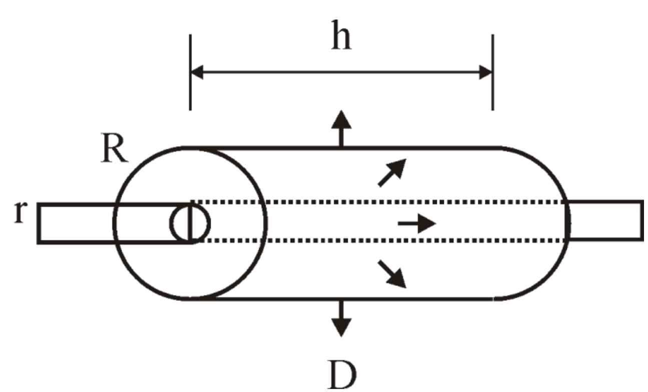
Gauss's law: $\int_A D \cdot da = q_e$,

D: electric flux density vector (coulombs/m^2 = C/m^2),電通密度向量

da : differential area with direction normal to the surface (m^2),方向垂直表面的微小面積

A: total closed surface area (m^2)總封閉表面積

q_e : algebraic sum of all charge enclosed by A (coulombs = C), A所包圍的電荷之代數和



Ex 3.6 Find the field of an infinite uniformly charfed straight round wire

Gauss's law: $\int_A D \cdot da = q_e$,

Draw a cylindrical Gaussian surface concentric with the wire and h meters long (the charge on the wire is q e/m of length). Considerations of symmetry indicate that D is radial and constant in magnitude over the curved portion of the cylinder (it is zero on the end caps).

$\int_A D \cdot da = D\,(2\,\pi\,Rh) = qh$

$D = q / (2\pi R)$, $R \geqq r$; $D = (a_r)\, q / (2\pi R)$, $R \geqq r$, (a_r) is a radially directed unit vector.

$D = \varepsilon E$, $\varepsilon = \varepsilon_r\, \varepsilon_o$,

Electric field: E (volts / meter) (E = force/q, force = $k\, q_1\, q_2 / r^2$)

$\varepsilon_o = 8.854 \times 10^{-12} = (1/36\pi) \times 10^{-9}$ (F/m)(permittivity:介電係數)

ε_r relative permittivity 相對介電係數

Voltage difference

$v_{\beta\alpha} = v_{P\beta} - v_{P\alpha} = -\int_{P\alpha}^{P\beta} E \cdot d\mathit{l}$

3.7線路電容(Line Capacitance: relates charge to voltage)

Voltage difference

$v_{\beta\alpha} = v_{P\beta} - v_{P\alpha} = -\int_{P\alpha}^{P\beta} E \cdot dl = -\int_{P\alpha}^{P\beta} D/\varepsilon \cdot dl$

$= -\int_{R\alpha}^{R\beta} q/(2\pi\varepsilon R)dR = (q/2\pi\varepsilon)\ln(R_\alpha/R_\beta)$

$v_{\beta\alpha} = v_{P\beta} - v_{P\alpha} = (1/2\pi\varepsilon)\Sigma^{n}_{i=1}\ (q_i)\ln(R_{\alpha i}/R_{\beta i})$

Assuming $q_1 + q_2 + \cdot + q_n = 0$, $P\alpha \to \infty$, $R_{\alpha 1} = R_{\alpha 2} = \cdot = R_{\alpha n} = R$

$v_\beta = (1/2\pi\varepsilon)\Sigma^{n}_{i=1}\ (q_i)\ln(1/R_{\beta i})$

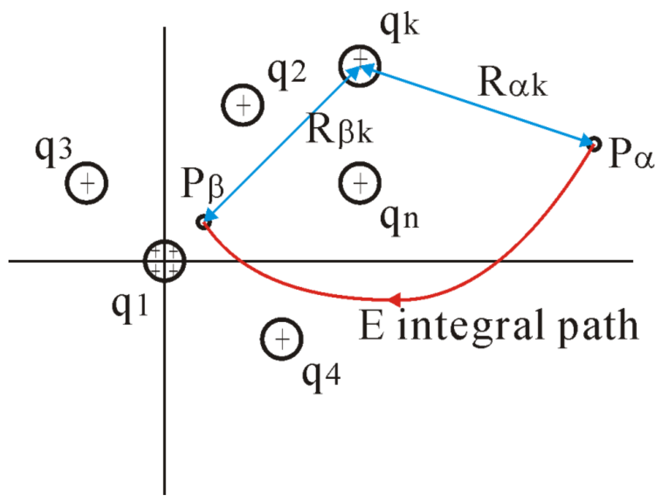
$v_1 = (1/2\pi\varepsilon)(q_1 \ln 1/R_{11} + q_2 \ln 1/R_{12} + \cdot + q_n \ln 1/R_{1n})$ for n lines

$v_1 = (1/2\pi\varepsilon)(q_1 \ln 1/r_1 + q_2 \ln 1/d_{12} + \cdot + q_n \ln 1/d_{1n})$

$v_k = (1/2\pi\varepsilon)(q_1 \ln 1/d_{k1} + q_2 \ln 1/d_{k2} + \cdot + q_k \ln 1/r_k + \cdot + q_n \ln 1/d_{kn})$

Matrix notation

$v = F\,q$, $q = C\,v$, $C = F^{-1}$



Ex 3.7 Calculate an expression for the capacitance per meter of a three-phase transmission line.

Assume that 1. conductors are equally spaced, D, and have equal radii r. 2. $q_a + q_b + q_c = 0$ ($c_a = c_b = c_c = c$, $v_a + v_b + v_c = 0$).

$v_a = (1/2\pi\varepsilon)(q_a \ln 1/r + q_b \ln 1/D + q_c \ln 1/D) = (1/2\pi\varepsilon)(q_a \ln 1/r - q_a \ln 1/D)$
$= (1/2\pi\varepsilon)(q_a \ln D/r)$

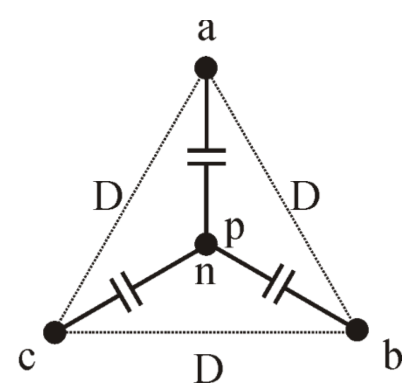
$C = q/v$, $c_a = c_b = c_c = c = (2\pi\varepsilon) / (\ln D/r)$ (F/m : 法拉/米) to neutral

$c_a \backslash = c_b \backslash = c_c \backslash = (2\pi\varepsilon) \ln(D_m/r)$ for one line transposition

$c_a \backslash = c_b \backslash = c_c \backslash = (2\pi\varepsilon) \ln(D_m/R_{GMR})$ for conductor bundling transposition

$D_m = (D_{12} D_{23} D_{13})^{1/3}$

$R^c{}_b = R_{GMR} = (r\, d_{12} d_{13} \cdot d_{1b})^{1/b}$, $b>1$; $R^c{}_b = R_{GMR} = r$, when $b=1$



Ex 3.8 Find phase-neutral capacitance and capacitive reactance per mile for a three-phase line with Dm=35.3 ft, conductor diameter = 1.25 in.

Solution: In air $\varepsilon = \varepsilon_r \varepsilon_o = 1 \times \varepsilon_o = 8.854 \times 10^{-12}$

$c\backslash = (2\pi\varepsilon) / (\ln Dm / r) = 2\pi \times 8.854 \times 10^{-12} / \ln[35.3 \times 12)/(1.25/2)]$

$= 8.53 \times 10^{-12}$ (F/m : 法拉/米)

$\omega\, c\backslash = 2\pi \times 60\text{Hz} \times 8.53 \times 10^{-12}$ mho/m $= 3.216 \times 10^{-9}$ mho/m

$= 3.216 \times 10^{-9} \times 1609.34$ mho/mile $= 5.175 \times 10^{-6}$ mho/mile

Phase-neutral reactance

$|Xc| = 1/(\omega\, c\backslash) = 1/(3.216 \times 10^{-9}) = 3.11 \times 10^{8}\ \Omega$-m

$= 1/(5.175 \times 10^{-6}) = 0.193$ MΩ-mile

It should be noted that we are neglecting the effect of the (conducting) earth under the transmission line. Charges are include in the earth, and these have some effect on the calculated values of capacitance. The effect is usually quite small for lines of reasonable height operating under normal non-fault conditions.

3.8典型參數值(Typical Parameter Values)

Conductors per phase (18-in. spacing) :	1(138kV),	2(345kV),	4(765kV)
Number of strands aluminum/steel :	54/7,	45/7,	54/19
Diameter (in.) :	0.977,	1.165,	1.424
Conductor GMR (ft) :	0.0329,	0.0386,	0.0479
Current-carrying capacity per conductor(A):	770,	1010,	1250
Bundle GMR-R_{GMR} (ft) :	0.0329,	0.2406,	0.6916
Flat phase spacing (ft) :	17.5,	26.0,	45.0
GMD phase spacing (ft) :	22.05,	32.76,	56.70
Inductance (H/m $\times 10^{-7}$) :	13.02,	9.83,	8.81
X_L (Ω/mile) :	0.789,	0.596,	0.535
Capacitance (F/m $\times 10^{-12}$) :	8.84,	11.59,	12.78
$\lvert X_C \rvert$ (MΩ-mile to neutral) :	0.186,	0.142,	0.129
Resistance (Ω/mile), dc, 50° C :	0.1618,	0.0539,	0.0190
Resistance (Ω/mile), 60Hz, 50° C :	0.1688,	0.0564,	0.0201
Surge impedance loading (MVA) :	50,	415,	2268

Three phase line-to-line 138 kVrms / 60Hz

Conductors per phase (18-in. spacing) : 1(138kV)

Number of strands aluminum/steel : 54/7,

Diameter (in.) : $0.977 \div 2 \div 12 = 0.0407$ ft,

Conductor GMR (ft):0.0329 = 0.0407×0.8?= $0.0317 = 0.0407 \times e^{-\mu r/4}$ $=0.0407 \times 0.7788$

Current-carrying capacity per conductor(A): 770,

Bundle GMR-R_{GMR} (ft) : r' =0.0329, r =0.0407=$0.977 \div 2 \div 12$

Flat phase spacing (ft) : 17.5,

GMD phase spacing (ft): 22.05 = $(17.5 \times 17.5 \times 2 \times 17.5)^{1/3} = 17.5 \times 1.26$

Inductance (H/m $\times 10^{-7}$) : 13.02 = $2 \times 10^{-7} \times \ln(22.05 / 0.0329)$

X_L (Ω/mile) : 0.789 = $2\pi \times 60 \times 13.02 \times 10^{-7} \times 1609.34$

Capacitance (F/m $\times 10^{-12}$): 8.84 =$2\pi \times 8.854 \times 10^{-12} / \ln(22.05 / 0.407)$

$|X_C|$ (MΩ-mile to neutral) : 0.186 = $1/(2\pi \times 60 \times 8.84 \times 10^{-12} \times 1609.34)$

Resistance (Ω/mile), dc, 50° C: $0.1618 = \rho \times 1609.34/[\pi(0.977 \times 2.54 \times 10^{-2}/2)^2]$, $\rho=4.863$

Three phase line-to-line 345 kVrms / 60Hz

Conductors per phase (18-in. spacing) : 2(345kV)

Number of strands aluminum/steel : 45/7,

Diameter (in.) : $1.165 \div 2 \div 12 = 0.0485$ ft,

Conductor GMR (ft): $0.0386 = 0.0485 \times 0.8? = 0.0378 = 0.0485 \times e^{-\mu r/4}$
$= 0.0485 \times 0.7788$

Current-carrying capacity per conductor(A): 1010,

Bundle GMR-R_{GMR} (ft) : $0.2406 = [0.0386 \times (18/12)]^{1/2}$,
$0.2697 = [0.0485 \times (18/12)]^{1/2}$

Flat phase spacing (ft) : 26.0,

GMD phase spacing (ft): $32.76 = (26.0 \times 26.0 \times 2 \times 26.0)^{1/3} =$
26.0×1.26

Inductance (H/m $\times 10^{-7}$) : $9.83 = 2 \times 10^{-7} \times \ln(32.76 / 0.2406)$

X_L (Ω/mile) : $0.596 = 2\pi \times 60 \times 9.83 \times 10^{-7} \times 1609.34$

Capacitance (F/m $\times 10^{-12}$): $11.59 = 2\pi \times 8.854 \times 10^{-12} / \ln(32.76 / 0.2697)$

$|X_C|$ (MΩ-mile to neutral) : $0.142 = 1/(2\pi \times 60 \times 11.59 \times 10^{-12} \times 1609.34)$

Resistance (Ω/mile),dc,50° C: $0.0539 = \rho \times 1609.34/[2 \times \pi(1.165 \times 2.54 \times 10^{-2}/2)^2]$, $\rho = 4.6066$

Three phase line-to-line 765 kVrms / 60Hz

Conductors per phase (18-in. = 1.5-ft spacing) : 4(765kV)

Number of strands aluminum/steel : 54/19,

Diameter (in.) : $1.424 \div 2 \div 12 = 0.0593$ ft,

Conductor GMR (ft): $0.0479 = 0.0593 \times 0.8? = 0.0462 = 0.0593 \times e^{-\mu r/4}$
$= 0.0593 \times 0.7788$

Current-carrying capacity per conductor(A): 1250,

Bundle GMR-R_{GMR} (ft) : $0.6916 = [0.0479 \times 1.5 \times 1.5 \times 1.5 \times \sqrt{2}]^{1/4}$,
$0.7294 = [0.0593 \times 1.5 \times 1.5 \times 1.5 \times \sqrt{2}]^{1/4}$,

Flat phase spacing (ft) : 45.0,

GMD phase spacing (ft): $56.7 = (45.0 \times 45.0 \times 2 \times 45.0)^{1/3} = 45.0 \times 1.26$

Inductance (H/m $\times 10^{-7}$) : $8.81 = 2 \times 10^{-7} \times \ln(56.7 / 0.6916)$

X_L (Ω/mile) : $0.535 = 2\pi \times 60 \times 8.81 \times 10^{-7} \times 1609.34$

Capacitance (F/m $\times 10^{-12}$): $12.78 = 2\pi \times 8.854 \times 10^{-12} / \ln(56.7 / 0.7294)$

$|X_C|$ (MΩ-mile to neutral) : $0.129 = 1/(2\pi \times 60 \times 12.78 \times 10^{-12} \times 1609.34)$

Resistance (Ω/mile),dc,50° C: $0.0190 = \rho \times 1609.34/[4 \times \pi(1.424 \times 2.54 \times 10^{-2}/2)^2]$, $\rho = 4.854$

3.9結論與習題(Summary)

For a three-phase line with transposition and bundling, the average per phase inductance (H/m) is given by

$l\backslash = (\mu_o /2\pi) \ln(D_m/R_{GMR})$ for conductor bundling transposition

$D_m = (D_{12}\, D_{23}\, D_{13})^{1/3}$

$r' = re^{-(\mu r/4)}$,$R_b = R_{GMR} = (r' d_{12} d_{13} \cdot d_{1b})^{1/b}$,b>1;$R_b = R_{GMR} = r'$,when b=1

The formula for average capacitance (F/m) to neutral is

$c\backslash = (2\pi\varepsilon) \ln(D_m/R_{GMR})$ for conductor bundling transposition

$D_m = (D_{12}\, D_{23}\, D_{13})^{1/3}$

$R^c_b = R_{GMR} = (r\, d_{12} d_{13} \cdot d_{1b})^{1/b}$, b>1 ; $R^c_b = R_{GMR} = r$, when b=1