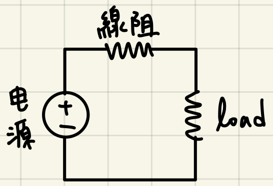
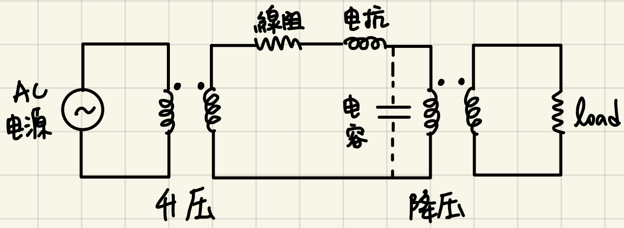
DC電力系統



AC電力系統



輸电線的參數 (被动元件)

R (电阻 Ω) 能量損失

L (电感 H) 有導線就有电感

C (电容 F)

$$R = \rho\left(\frac{l}{A}\right) = \frac{l_{\text{長度}}}{\mu A_{\text{截面積}}}$$

導磁 ≠ 導电

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① 無限長电線的磁通鏈

$$\lambda = \overset{\text{內(自)}}{\lambda_2} + \overset{\text{內(互)}}{\lambda_1} = \frac{\mu_0 i}{2\pi}$$

② 無限長电線的磁通鏈 (多導体)

③ a相.b相 c相 互擾 (單一導体)

④ a相.b相 c相 互擾 (每相多導体)

⑤ 移位 (多導体互擾) ：先求 $r' = re^{-\frac{\mu r}{4}}$

再求 $R_{GMR} = ?$

3.輸電線參數(Transmission-Line Parameters)

- 3.0簡介(Introduction)
- 3.1磁學回顧(Review of Magnetics)
- 3.2無限長直電線的磁通鏈(Flux Linkages of Infinite Straight Wire)
- 3.3多導體情況下的磁通鏈(Flux Linkages of Multi-Conductors)
- 3.4捆束導體(Conductor Bundling)
- 3.5移位(Transposition)
- 3.6電場回顧(Review of Electric Fields)
- 3.7線路電容(Line Capacitance)
- 3.8典型參數值(Typical Parameter Values)
- 3.9結論與習題(Summary)

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: $\rho = 1.64 \times 10^{-8}$ Ωm,

Copper: $\rho = 1.72 \times 10^{-8}$ Ωm, $R=1.72 \times 10^{-8} \times 1\text{km} / \pi(0.01\text{m})^2 = 0.0547\Omega$

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

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

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

Paper: $\rho = 10^{10}$ Ωm, Mica (雲母): $\rho = 5 \times 10^{11}$ Ωm, Glass: $\rho = 10^{12}$ Ωm, Teflon: $\rho = 3 \times 10^{12}$ Ωm, Air: $\rho = 1.5 \times 10^{14}$ 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=ρ(*l/A*), ρ (resistivity:電阻率Ωm), σ = 1/ρ (conductivity: 導電率1/Ωm =A/(V × m))

Skin Depth,δ = 1/(πfμσ)$^{0.5}$, μ_o = 4π × 10^{-7} (H/m)(permeability:導磁係數)

Silver: σ = 6.17x10^7 , δ =8.27mm (at 60Hz), δ =0.064mm (at 1MHz)

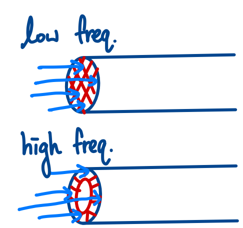
Copper: σ = 5.8x10^7 , δ =8.53mm (at 60Hz), δ =0.066mm (at 1MHz)

Aluminum: σ =3.54x10^7 ,δ =10.92mm (at 60Hz), δ =0.084mm (at 1MHz)

Gold: σ = 4.1x10^7 , δ =10.14mm (at 60Hz), δ =0.079mm (at 1MHz)

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

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



ε_o = (1/36π) × 10^{-9} (F/m)(permittivity:介電係數)

Speed of light: C=1/(μ_o ε_o)$^{0.5}$ =3x10^8 m/s, [(H・F)=(s^2), 亨利・法拉= s^2]

介电係数 磁係数

Wave length of 60Hz: λ = C/f = 5x10^6 m,

3.1磁學回顧(Review of Magnetics)

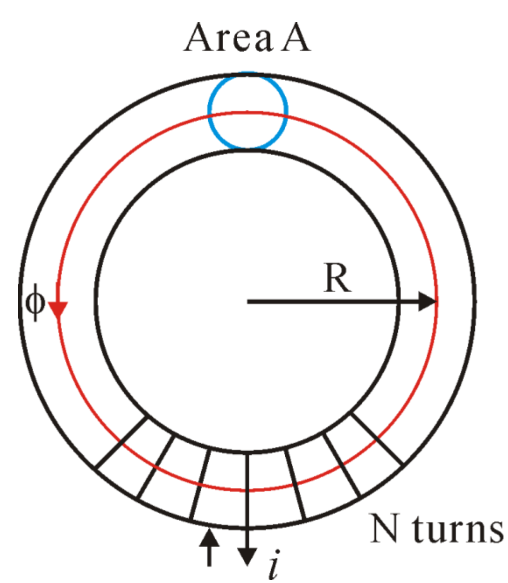
Ampere's Circuital Law: $\mathcal{F} = \oint \mathrm{H} \cdot \mathrm{d}l = \mathrm{N}i$ 磁動勢

磁通密度

$\mathrm{B} = \mu\,\mathrm{H}$, $\mathrm{B} = \Phi/\mathrm{A}$, Φ: flux, B: flux density (webers/m^2), H: magnetic field intensity (A · turn/m)

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

Ex3.1 Calculate the inductance.



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

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

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

$L = \lambda/i = \mathrm{N}\Phi/i = (\mu\mathrm{AN}^2/l) = \mu\mathrm{AN}^2/(2\pi\mathrm{R})$

inductance: relates flux linkage to current

$e_{ind} = L\frac{di}{dt} = N\frac{d\phi}{dt}$ $\phi = BA = \mu HA = \mu\frac{Ni}{l}A$

$\frac{L\cancel{i}}{\cancel{t}} = \frac{N\phi}{t} = N\mu\frac{N\cancel{i}}{l\cancel{t}}A$

$L = \frac{N^2\mu A}{l}$

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

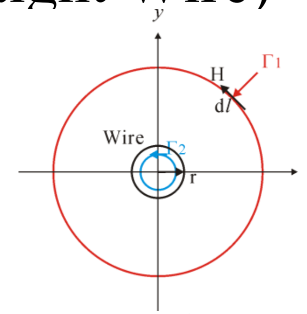


Figure 3.2: wire carrying current

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

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

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

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

線外 : $\mu_o \int_r^R H dx = \mu_o \int_r^R \frac{i}{2\pi x} dx = \frac{\mu_o i}{2\pi} \int \frac{1}{x} dx = \frac{\mu_o i}{2\pi} \ln\left(\frac{R}{r}\right)$

線內 : $\mu_r \mu_o \int_0^r \frac{x}{2\pi r^2} \times \frac{\pi x^2}{\pi r^2} i dx = \frac{\mu_r \mu_o i}{2\pi r^4} \int_0^r x^3 dx = \frac{\mu_r \mu_o i}{2\pi r^4} \times \frac{r^4}{4} = \frac{\mu_r \mu_o i}{8\pi}$

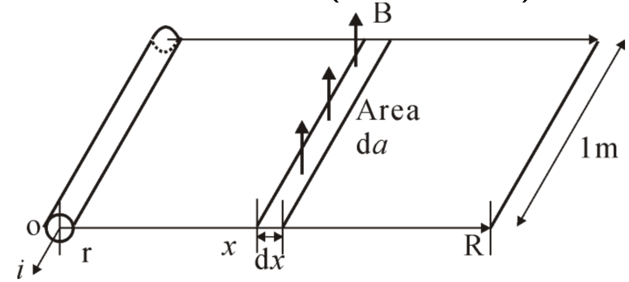


Figure 3.3: infinite wire of radius r, find flux crossing rectangle.

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: $R \to \infty$ 找不到)

Case 2 ($x \leq r$, $\boxed{N = \overset{<1}{\pi x^2/\pi r^2}}$): $\lambda_2 = \mu_r \mu_o \int_0^r (x/2\pi r^2)(\pi x^2/\pi r^2) i\, dx = \mu_r \mu_o i/(8\pi)$

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 :

(自)內 (互)外

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

$\lambda_1=\phi_1=B_1A_1=\mu_0 H_1 A_1$

$\lambda_2=\phi_2=B_2A_2=\mu_r\mu_0 H_2 A_2$

$H_1A_1=\int_A H(x)dx=\int_A \frac{i}{2\pi x}dx$

$H_2A_2=\int_A H(x)=dx=\int_A \frac{x}{2\pi r^2}\left(\frac{\pi x^2}{\pi r^2}\right) i\,dx$

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

從 wire 1 的視角出發的自感　　從 wire 1 的視角出發的外感

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

distance

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

$$+(\mu_o/2\pi)[i_1(\ln(R_1)+i_2\ln(R_2)+\cdot\ \ \cdot+i_n\ln(R_n)]$$

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

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

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

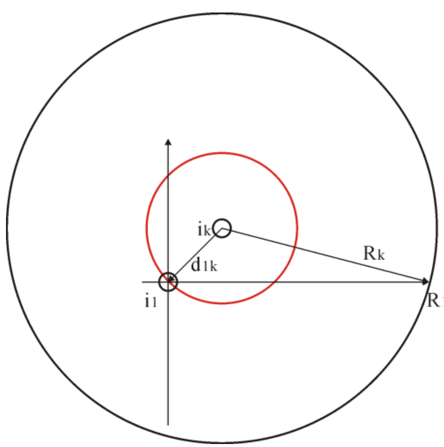
$i_1\ln(\frac{R}{r_1})=i_1(\ln R-\ln r_1)$

$i_2\ln(\frac{R}{r_2})=i_2(\ln R-\ln r_2)$ $\Rightarrow$ $i_n\ln(\frac{R}{r_n})=i_n(\ln R-\ln r_n)$

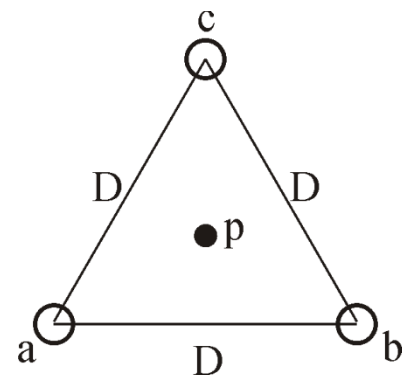
$\vdots$

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

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



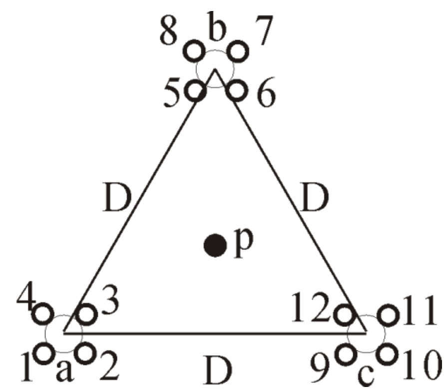
Ex3.2 Calculate the inductance per meter of each phase of a three-phase transmission line.



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. $D = 1\text{m}$, $r = 0.01\text{m}$.

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

$l_a = ?$

3.4捆束導體(Conductor Bundling)

$$\lambda_1 = (\mu_o/2\pi)\{ (i_a/4)[\mu_r/4 + \ln(1/r) + \ln(1/d_{12}) + \ln(1/d_{13}) + \ln(1/d_{14})]$$
$$+ (i_b/4)[\ln(1/d_{15}) + \ln(1/d_{16}) + \ln(1/d_{17}) + \ln(1/d_{18})]$$
$$+ (i_c/4)[\ln(1/d_{19}) + \ln(1/d_{1,10}) + \ln(1/d_{1,11}) + \ln(1/d_{1,12})] \}$$
$$= (\mu_o/2\pi)(i_a \ln 1/R_{GMR} + i_b \ln 1/D_{1b} + i_c \ln 1/D_{1c}$$

單相多導体

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

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

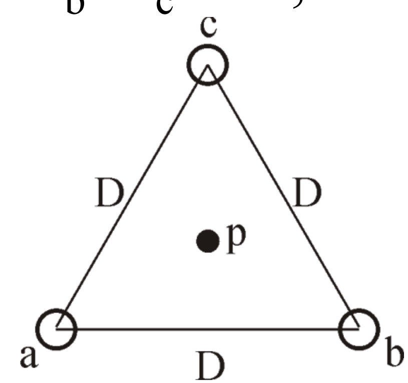
Assuming $D_{1b} = D_{1c} = D$ (geometric mean distance), $i_a + i_b + i_c = 0$,

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

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 ,

$d_{12} = d_{13} = d_{23} = 50$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.

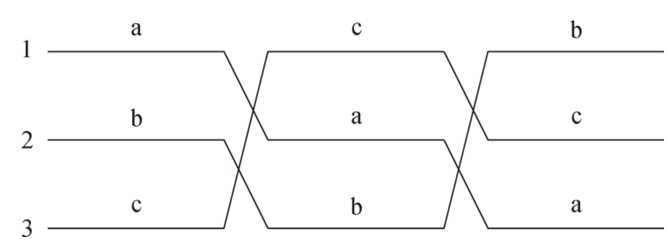
$\lambda_a\backslash = (\lambda_{a1} + \lambda_{a2} + \lambda_{a3})/3$, $D_m = (d_{12}\, d_{23}\, d_{13})^{1/3}$,

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

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

$l_a\backslash = l_b\backslash = l_c\backslash = (\mu_o/2\pi) \ln(D_m/r')$ 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.

1.27 cm

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

(b) $Dm = (\,20 \text{ ft} \times\ 20 \text{ ft} \times\ 40 \text{ ft}\,)^{1/3} = 25.2$ ft

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

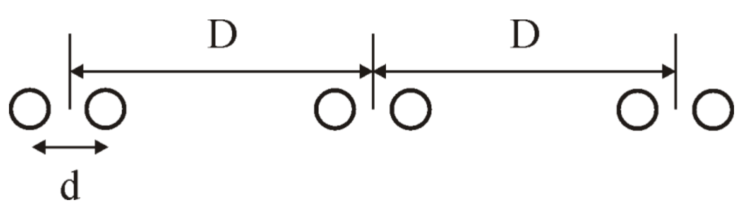
$= 9.47 \times 10^{-7}$ H/m

$\approx 10^{-6}\, H/m \;=\; 1\mu H/m \;=\; 1 mH/km$ $\boxed{\text{很大}}$

$X = \omega L$

$= 377 \times 1 mH/km$

$= 0.377\, H/km$



3.8典型參數值(Typical Parameter Values)

Conductors per phase (18-in. spacing) :	1(138kV),	2(345kV), TW max	4(765kV) next 69kV
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
$\|X_C\|$ (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 (線权) (138kV)

Number of strands aluminum/steel : 54/7,

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

根據Fe&Al的含量估算

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

Current-carrying capacity per conductor(A): 770, $1\ mm^2 \approx 7A$

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: $0.1618 = \rho \times 1609.34/[\pi(0.977 \times 2.54 \times 10^{-2}/2)^2]$, $\rho = 4.863 \times 10^{-8}$

Resistance (Ω/mile), 60Hz, 50˚C : $0.1688 = 0.1618 \times 1.0433$

Surge impedance loading (MVA): 50 ?$= 61.4 = 1 \times \sqrt{3} \times 138 \times 0.77/3$ (MVA)

一個相

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): $32.76 = (26.0 \times 26.0 \times 2 \times 26.0)^{1/3} = 26.0 \times 1.26$

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: $0.0539 = \rho \times 1609.34/[2 \times \pi(1.165 \times 2.54 \times 10^{-2}/2)^2]$, $\rho = 4.6066 \times 10^{-8}$

Resistance (Ω/mile), 60Hz, 50°C : $0.0564 = 0.0539 \times 1.0464$

Surge impedance loading (MVA):$415? = 402.3 = 2 \times \sqrt{3} \times 345 \times 1.010/3$ (MVA)

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: $0.0190 = \rho \times 1609.34/[4 \times \pi(1.424 \times 2.54 \times 10^{-2}/2)^2]$, $\rho = 4.854 \times 10^{-8}$

Resistance (Ω/mile), 60Hz, 50°C : $0.0201 = 0.0190 \times 1.0579$

Surge impedance loading (MVA) : 2268 ?= $2208.3 = 4 \times \sqrt{3} \times 765 \times 1.250/3$ (MVA)

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 $b=1$