Cable Systems - Postive/Negative Seq Impedance

Nomenclature:

GMD   - geometrical mead distance between conductors; depends on construction of the T-line or cable feeder

GMR   - geometric mean raduius of conductor (single conductor, not bundle);

values are given in tables with conductor properties

▶ GMR and GMD calculations and Estimations ─────────────────────────────────

▶ Conductor Reactance ───
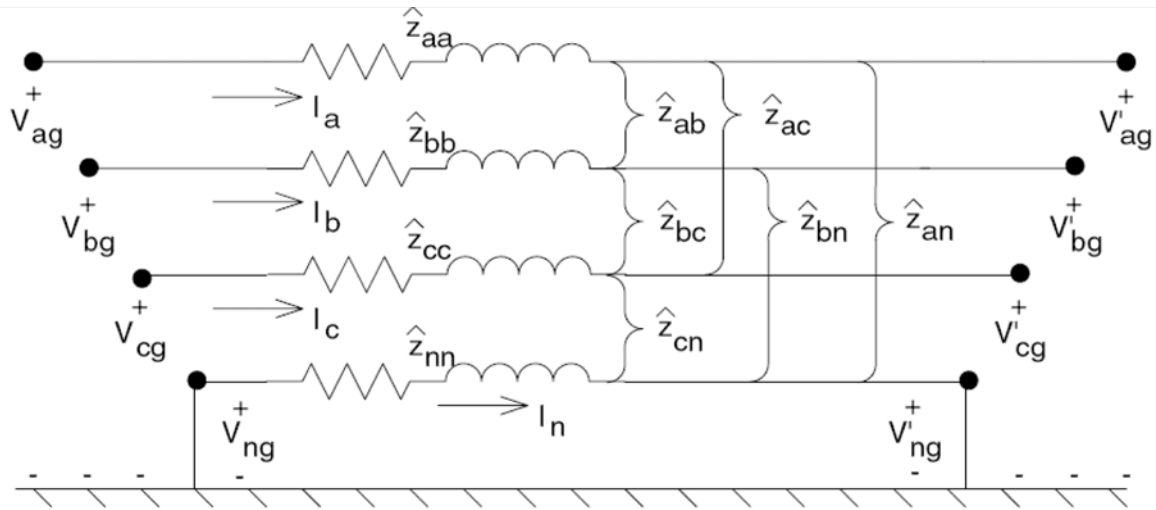
$$z_{primitive} = \begin{pmatrix} z_{aa} & z_{ab} & z_{ac} & z_{an1} & z_{an2} & z_{an3} \\ z_{ba} & z_{bb} & z_{bc} & z_{bn1} & z_{bn2} & z_{bn3} \\ z_{ca} & z_{cb} & z_{cc} & z_{cn1} & z_{cn2} & z_{cn3} \\ z_{n1a} & z_{n1b} & z_{n1c} & z_{n1n1} & z_{n1n2} & z_{n1n3} \\ z_{n2a} & z_{n2b} & z_{n2c} & z_{n2n1} & z_{n2n2} & z_{n2n3} \\ z_{n3a} & z_{n3b} & z_{n3c} & z_{n3n1} & z_{n3n2} & z_{n3n3} \end{pmatrix}$$

$$z_{ij} = \begin{pmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{pmatrix} \qquad Z_{in} = \begin{pmatrix} z_{an1} & z_{an2} & z_{an3} \\ z_{bn1} & z_{bn2} & z_{bn3} \\ z_{cn1} & z_{cn2} & z_{cn3} \end{pmatrix}$$

$$Z_{nj} = \begin{pmatrix} z_{n1a} & z_{n1b} & z_{n1c} \\ z_{n2a} & z_{n2b} & z_{n2c} \\ z_{n3a} & z_{n3b} & z_{n3c} \end{pmatrix} \qquad z_{nn} = \begin{pmatrix} z_{n1n1} & z_{n1n2} & z_{n1n3} \\ z_{n2n1} & z_{n2n2} & z_{n2n3} \\ z_{n3n1} & z_{n3n2} & z_{n3n3} \end{pmatrix}$$

$$z_{primitive} = \begin{pmatrix} z_{ij} & z_{in} \\ z_{nj} & z_{nn} \end{pmatrix}$$

3PH, 4W, grounded WYE line segement

$$\begin{pmatrix} Vs_{ag} \\ Vs_{bg} \\ Vs_{cg} \\ Vs_{ng} \end{pmatrix} = \begin{pmatrix} Vr_{ag} \\ Vr_{bg} \\ Vr_{cg} \\ Vr_{ng} \end{pmatrix} + \begin{pmatrix} z_{aa} & z_{ab} & z_{ac} & z_{an} \\ z_{ba} & z_{bb} & z_{bc} & z_{bn} \\ z_{ca} & z_{cb} & z_{cc} & z_{cn} \\ z_{na} & z_{nb} & z_{nc} & z_{nn} \end{pmatrix} \cdot \begin{pmatrix} I_a \\ I_b \\ I_c \\ I_n \end{pmatrix}$$

$$\begin{pmatrix} Vs_{abc} \\ Vs_{ng} \end{pmatrix} = \begin{pmatrix} Vr_{abc} \\ Vr_{ng} \end{pmatrix} + \begin{pmatrix} z_{ij} & z_{in} \\ z_{nj} & z_{nn} \end{pmatrix} \cdot \begin{pmatrix} I_{abc} \\ I_n \end{pmatrix}$$

Because Vs_{ng} and Vr_{ng} are grounded, then $Vs_{ng} = 0$ and $Vr_{ng} = 0$

$$Vs_{abc} = Vr_{abc} + z_{ij} \cdot I_{abc} + z_{in} \cdot I_n$$

$$0 = 0 + z_{nj} \cdot I_{abc} + z_{nn} \cdot I_n$$

$$I_n = -z_{nn}^{-1} \cdot z_{nj} \cdot I_{abc}$$

$$Vs_{abc} = Vr_{abc} + z_{ij} \cdot I_{abc} + z_{in} \cdot \left(-z_{nn}^{-1} \cdot z_{nj} \cdot I_{abc} \right)$$

$$Vs_{abc} = Vr_{abc} + \left(z_{ij} - z_{in} \cdot z_{nn}^{-1} \cdot z_{nj}\right) \cdot I_{abc}$$

$$Z_{abc} = z_{ij} - z_{in} \cdot z_{nn}^{-1} \cdot z_{nj}$$

$$Vs_{abc} = Vr_{abc} + Z_{abc} \cdot I_{abc}$$

Sequence values

$$a_s := 1e^{j \cdot 120deg}$$

$$\begin{pmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a_s^2 & a_s \\ 1 & a_s & a_s^2 \end{pmatrix} \cdot \begin{pmatrix} Vlg_0 \\ Vlg_1 \\ Vlg_2 \end{pmatrix}$$

$$A_s := \begin{pmatrix} 1 & 1 & 1 \\ 1 & a_s^2 & a_s \\ 1 & a_s & a_s^2 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & -0.5 - 0.866j & -0.5 + 0.866j \\ 1 & -0.5 + 0.866j & -0.5 - 0.866j \end{pmatrix}$$

$$Vlg_{abc} = A_s \cdot Vlg_{012}$$

$$I_{abc} = A_s \cdot I_{012}$$

$$Vlg_{012} = A_s^{-1} \cdot Vlg_{abc}$$

$$A_s^{-1} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a_s^2 & a_s \\ 1 & a_s & a_s^2 \end{pmatrix}^{-1} = \frac{1}{3} \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & a_s & a_s^2 \\ 1 & a_s^2 & a_s \end{pmatrix}$$

$$A_s^{-1} = \begin{pmatrix} 0.333 & 0.333 & 0.333 \\ 0.333 & -0.167 + 0.289j & -0.167 - 0.289j \\ 0.333 & -0.167 - 0.289j & -0.167 + 0.289j \end{pmatrix}$$

$$\mathbf{Vs_{abc}} = \mathbf{Vr_{abc}} + \mathbf{Z_{abc}} \cdot \mathbf{I_{abc}}$$

$$\mathbf{A_s}^{-1} \cdot \mathbf{Vs_{abc}} = \mathbf{A_s}^{-1} \cdot \mathbf{Vr_{abc}} + \mathbf{A_s}^{-1} \cdot \mathbf{Z_{abc}} \cdot \mathbf{A_s} \cdot \mathbf{I_{012}}$$

$$\mathbf{Vlg_{s\_012}} = \mathbf{Vlg_{r\_012}} + \mathbf{Z_{012}} \cdot \mathbf{I_{012}}$$

$$\mathbf{Z_{012}} = \mathbf{A_s}^{-1} \cdot \mathbf{Z_{abc}} \cdot \mathbf{A_s} \qquad \mathbf{Z_{012}} = \begin{pmatrix} Z_{00} & Z_{01} & Z_{02} \\ Z_{10} & Z_{11} & Z_{12} \\ Z_{20} & Z_{21} & Z_{22} \end{pmatrix}$$

For symetrical, transposed line:

$$z_s = \frac{1}{3} \cdot \left(z_{aa} + z_{bb} + z_{cc} \right) \cdot \frac{\Omega}{\text{mile}}$$

$$z_m = \frac{1}{3} \cdot \left(z_{ab} + z_{bc} + z_{ca} \right) \cdot \frac{\Omega}{\text{mile}}$$

$$\mathbf{Z_{abc}} = \begin{pmatrix} z_s & z_m & z_m \\ z_m & z_s & z_m \\ z_m & z_m & z_s \end{pmatrix} \cdot \frac{\Omega}{\text{mile}}$$

Consequently:

$$z_{00} = \left(z_s + 2 \cdot z_m \right) \cdot \frac{\Omega}{\text{mile}}$$

$$z_{11} = z_{22} = \left(z_s - z_m \right) \cdot \frac{\Omega}{\text{mile}}$$

Or by applying GMD and GMR calcualtions for system of $n_{cond} \cdot n_{cond}$:

Between phases: $D_{ij} = GMD_{ij} = \sqrt[3]{D_{ab} \cdot D_{bc} \cdot D_{ca}} \cdot \text{ft}$

Phase and neutral: $D_{in} = GMD_{in} = \sqrt[3]{D_{an} \cdot D_{bn} \cdot D_{cn}} \cdot \text{ft}$

$$z_{ii} = r_i + 0.0953 + j \cdot 0.12134 \cdot \left(\ln\left(\frac{1}{GMR_i} \right) + 7.93402 \right) \frac{\Omega}{\text{mile}}$$

$$z_{nn} = r_i + 0.0953 + j \cdot 0.12134 \cdot \left(\ln\left(\frac{1}{GMR_n} \right) + 7.93402 \right) \frac{\Omega}{mile}$$

$$z_{ij} = 0.0953 + j \cdot 0.12134 \cdot \left(\ln\left(\frac{1}{D_{ij}} \right) + 7.93402 \right) \frac{\Omega}{mile}$$
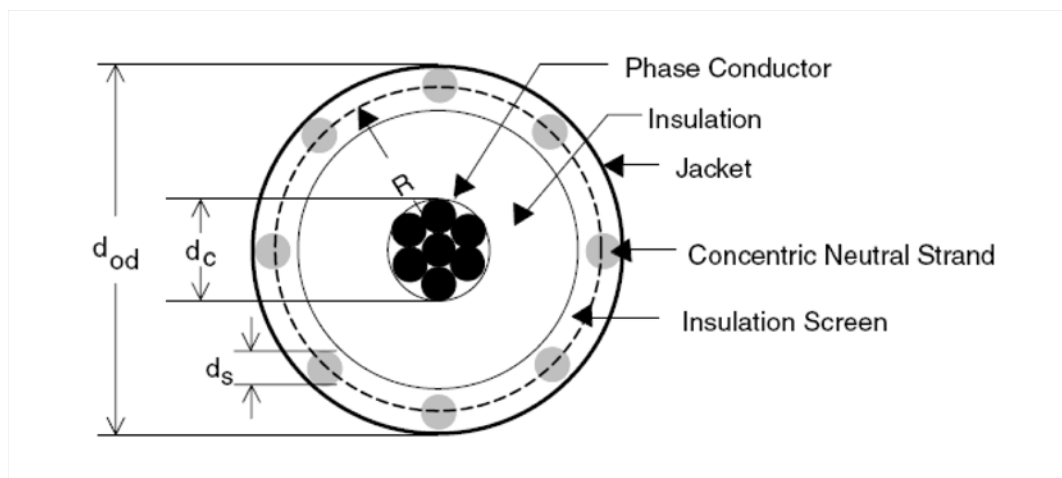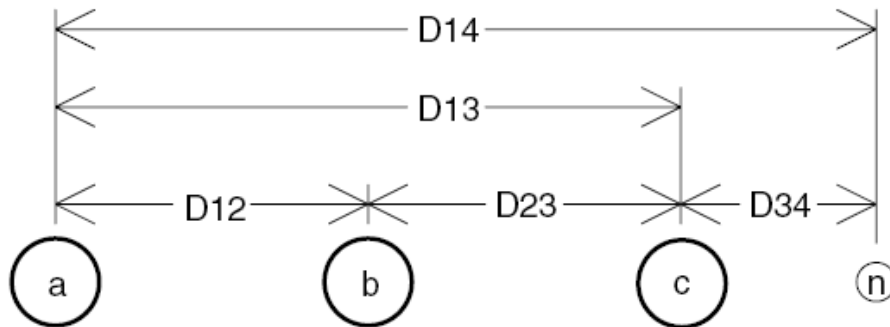
$$z_{in} = 0.0953 + j \cdot 0.12134 \cdot \left(\ln\left(\frac{1}{D_{in}} \right) + 7.93402 \right) \frac{\Omega}{mile}$$

$$z_{00} = \left(z_{ii} + 2 \cdot z_{ij} - 3 \cdot \frac{z_{in}^2}{z_{nn}} \right) \cdot \frac{\Omega}{mile}$$

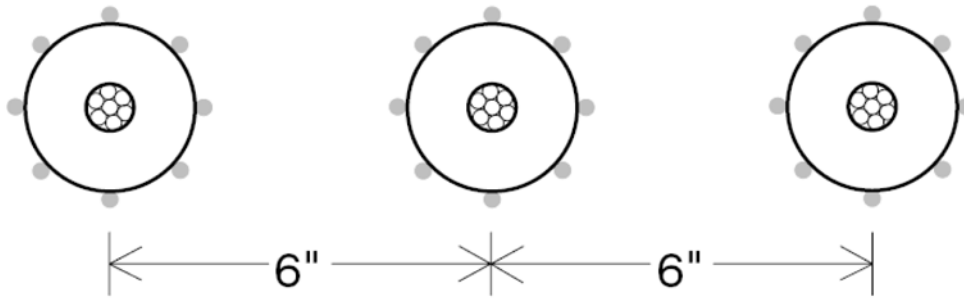$$z_{11} = z_{22} = \left(z_{ii} - z_{ij} \right) \cdot \frac{\Omega}{mile}$$

$$z_{11} = z_{22} = r_i + j \cdot 0.12134 \cdot \ln\left(\frac{D_{ij}}{GMR_i} \right) \cdot \frac{\Omega}{mile}$$

Series Impedance for Underground Line

Where:

d_c - phase conductor diameter [in]

d_{od} - nominal diameter over the concentric neutrals of the cable [in]

d_s - diameter of a concentric neutral strand [in]

GMR_c - geometric mean radius of the phase conductor [ft]

GMR_s - geometric mean radius of a neutral strand [ft]

$$GMR_{cn} = \sqrt[k]{GMR_s \cdot k \cdot R^{k-1}} \cdot ft$$

r_c - resistance of the phase conductor [$\frac{\Omega}{mile}$]

r_s - resistance of a solid neutral strand [$\frac{\Omega}{mile}$]

k - number of concentric neutral strands

Example:

Phase: (1)   (2)   (3)

Neutral: (4)   (5)   (6)

Cable is 250kcmil, 15kV, Al with (13)-#14 annealed, coated copper wires (1/3 neutral),
$OD_{cab} := 1.29 in$, $k := 13$ $f := 60 Hz$

For cable: 250 kcmil AA:

$$GMR_{abc} := 0.0171$$

$$OD_{cond} := 0.567 in$$

$$r_c := 0.4100 \frac{\Omega}{mile}$$

For neutral strand: #14 Copper

$$GMR_s := 0.00208 ft$$

$$d_s := 0.0641 in$$

$$r_{cs} := 14.8722 \frac{\Omega}{mile}$$

$$R := \frac{OD_{cab} - d_s}{2} = 0.0511 \cdot ft$$

$$GMR_{cn} := \sqrt[13]{GMR_s \cdot 13 \cdot R^{12}} \cdot \frac{1}{ft} = 0.04864$$

$$r_{cn} := \frac{r_{cs}}{k} = 1.14402 \cdot \frac{\Omega}{mile}$$

$D_{12} = D_{21} = D_{45} = D_{54} = 0.5\text{ft}$ $\qquad$ $D_{12} := 0.5$ $\qquad$ $D_{45} := 0.5$

$D_{23} = D_{32} = D_{56} = D_{65} = 0.5\text{ft}$

$D_{31} = D_{13} = D_{64} = D_{46} = 1.0\text{ft}$ $\qquad$ $D_{31} := 1.0$ $\qquad$ $D_{46} := 1$

$D_{14} = D_{25} = D_{36} = R = 0.0511\text{ft}$ $\qquad$ $D_{14} := 0.0511$

$D_{15} = D_{51} = 0.5\text{ft}$ $\qquad$ $D_{15} := 0.5$

$D_{26} = D_{62} = 0.5\text{ft}$

$D_{61} = D_{16} = 1.0\cdot\text{ft}$ $\qquad$ $D_{16} := 1$

$$z_{11} := r_c + 0.0953\cdot\frac{\Omega}{\text{mile}} + j\cdot 0.12134\cdot\left(\ln\left(\frac{1}{GMR_{abc}}\right) + 7.93402\right)\frac{\Omega}{\text{mile}} = (0.505 + 1.456j)\cdot\frac{\Omega}{\text{mile}}$$

$$z_{22} := z_{11}$$

$$z_{33} := z_{11}$$

$$z_{44} := r_{cn} + 0.0953\cdot\frac{\Omega}{\text{mile}} + j\cdot 0.12134\cdot\left(\ln\left(\frac{1}{GMR_{cn}}\right) + 7.93402\right)\frac{\Omega}{\text{mile}} = (1.239 + 1.33j)\cdot\frac{\Omega}{\text{mile}}$$

$$z_{55} := z_{44}$$

$$z_{66} := z_{44}$$

$$z_{12} := 0.0953\cdot\frac{\Omega}{\text{mile}} + j\cdot 0.12134\cdot\left(\ln\left(\frac{1}{D_{12}}\right) + 7.93402\right)\frac{\Omega}{\text{mile}} = (0.095 + 1.047j)\cdot\frac{\Omega}{\text{mile}}$$

$$z_{21} := z_{12} \qquad z_{23} := z_{12} \qquad z_{32} := z_{23}$$

$$z_{13} := 0.0953\cdot\frac{\Omega}{\text{mile}} + j\cdot 0.12134\cdot\left(\ln\left(\frac{1}{D_{31}}\right) + 7.93402\right)\frac{\Omega}{\text{mile}} = (0.095 + 0.963j)\cdot\frac{\Omega}{\text{mile}}$$

$$z_{31} := z_{13}$$

$$z_{14} := 0.0953\cdot\frac{\Omega}{\text{mile}} + j\cdot 0.12134\cdot\left(\ln\left(\frac{1}{D_{14}}\right) + 7.93402\right)\frac{\Omega}{\text{mile}} = (0.095 + 1.324j)\cdot\frac{\Omega}{\text{mile}}$$

$$z_{41} := z_{14} \qquad z_{25} := z_{14} \qquad z_{52} := z_{25} \qquad z_{36} := z_{14} \qquad z_{63} := z_{36}$$

$$z_{15} := 0.0953 \cdot \frac{\Omega}{\text{mile}} + j \cdot 0.12134 \cdot \left(\ln\left(\frac{1}{D_{15}}\right) + 7.93402 \right) \frac{\Omega}{\text{mile}} = (0.095 + 1.047j) \cdot \frac{\Omega}{\text{mile}}$$

$$z_{51} := z_{15} \quad z_{24} := z_{15} \quad z_{42} := z_{24} \quad z_{35} := z_{15} \quad z_{53} := z_{35} \quad z_{26} := z_{15} \quad z_{62} := z_{26}$$

$$z_{16} := 0.0953 \cdot \frac{\Omega}{\text{mile}} + j \cdot 0.12134 \cdot \left(\ln\left(\frac{1}{D_{16}}\right) + 7.93402 \right) \frac{\Omega}{\text{mile}} = (0.095 + 0.963j) \cdot \frac{\Omega}{\text{mile}}$$

$$z_{61} := z_{16} \quad z_{34} := z_{16} \quad z_{43} := z_{34}$$

$$z_{45} := 0.0953 \cdot \frac{\Omega}{\text{mile}} + j \cdot 0.12134 \cdot \left(\ln\left(\frac{1}{D_{45}}\right) + 7.93402 \right) \frac{\Omega}{\text{mile}} = (0.095 + 1.047j) \cdot \frac{\Omega}{\text{mile}}$$

$$z_{54} := z_{45} \quad z_{56} := z_{45} \quad z_{65} := z_{56}$$

$$z_{46} := 0.0953 \cdot \frac{\Omega}{\text{mile}} + j \cdot 0.12134 \cdot \left(\ln\left(\frac{1}{D_{46}}\right) + 7.93402 \right) \frac{\Omega}{\text{mile}} = (0.095 + 0.963j) \cdot \frac{\Omega}{\text{mile}}$$

$$z_{64} := z_{46}$$

$$\mathbf{z_{ij}} := \begin{pmatrix} z_{11} & z_{12} & z_{13} \\ z_{21} & z_{22} & z_{23} \\ z_{31} & z_{32} & z_{33} \end{pmatrix} = \begin{pmatrix} 0.505 + 1.456j & 0.095 + 1.047j & 0.095 + 0.963j \\ 0.095 + 1.047j & 0.505 + 1.456j & 0.095 + 1.047j \\ 0.095 + 0.963j & 0.095 + 1.047j & 0.505 + 1.456j \end{pmatrix} \cdot \frac{\Omega}{\text{mile}}$$

$$\mathbf{z_{in}} := \begin{pmatrix} z_{14} & z_{15} & z_{16} \\ z_{24} & z_{25} & z_{26} \\ z_{34} & z_{35} & z_{36} \end{pmatrix} = \begin{pmatrix} 0.095 + 1.324j & 0.095 + 1.047j & 0.095 + 0.963j \\ 0.095 + 1.047j & 0.095 + 1.324j & 0.095 + 1.047j \\ 0.095 + 0.963j & 0.095 + 1.047j & 0.095 + 1.324j \end{pmatrix} \cdot \frac{\Omega}{\text{mile}}$$

$$\mathbf{z_{nj}} := \begin{pmatrix} z_{41} & z_{42} & z_{43} \\ z_{51} & z_{52} & z_{53} \\ z_{61} & z_{62} & z_{63} \end{pmatrix} = \begin{pmatrix} 0.095 + 1.324j & 0.095 + 1.047j & 0.095 + 0.963j \\ 0.095 + 1.047j & 0.095 + 1.324j & 0.095 + 1.047j \\ 0.095 + 0.963j & 0.095 + 1.047j & 0.095 + 1.324j \end{pmatrix} \cdot \frac{\Omega}{\text{mile}}$$

$$\mathbf{z_{nn}} := \begin{pmatrix} z_{44} & z_{45} & z_{46} \\ z_{54} & z_{55} & z_{56} \\ z_{64} & z_{65} & z_{66} \end{pmatrix} = \begin{pmatrix} 1.239 + 1.33j & 0.095 + 1.047j & 0.095 + 0.963j \\ 0.095 + 1.047j & 1.239 + 1.33j & 0.095 + 1.047j \\ 0.095 + 0.963j & 0.095 + 1.047j & 1.239 + 1.33j \end{pmatrix} \cdot \frac{\Omega}{\text{mile}}$$

$$z_{abc} := z_{ij} - z_{in} \cdot z_{nn}^{-1} \cdot z_{nj}$$

$$z_{abc} = \begin{pmatrix} 0.798 + 0.446j & 0.319 + 0.033j & 0.285 - 0.014j \\ 0.319 + 0.033j & 0.789 + 0.404j & 0.319 + 0.033j \\ 0.285 - 0.014j & 0.319 + 0.033j & 0.798 + 0.446j \end{pmatrix} \cdot \frac{\Omega}{\text{mile}}$$

$$z_{012} := A_s^{-1} \cdot z_{abc} \cdot A_s$$

$$z_{012} = \begin{pmatrix} 1.4106 + 0.4666i & -0.0028 - 0.0081i & -0.0056 + 0.0065i \\ -0.0056 + 0.0065i & 0.4874 + 0.4151i & -0.0264 + 0.0451i \\ -0.0028 - 0.0081i & 0.0523 + 0.0003i & 0.4874 + 0.4151i \end{pmatrix} \cdot \frac{\Omega}{\text{mile}}$$

Shunt capacitance

Primitive matrices are used for UG cables and OH lines. Sometimes, if cable system is simple (3/c or 3-1/c only), capacitance of cables are calculated directly from physical properties.

$$p_{primitive} = \begin{pmatrix} p_{aa} & p_{ab} & p_{ac} & p_{an1} & p_{an2} & p_{an3} \\ p_{ba} & p_{bb} & p_{bc} & p_{bn1} & p_{bn2} & p_{bn3} \\ p_{ca} & p_{cb} & p_{cc} & p_{cn1} & p_{cn2} & p_{cn3} \\ p_{n1a} & p_{n1b} & p_{n1c} & p_{n1n1} & p_{n1n2} & p_{n1n3} \\ p_{n2a} & p_{n2b} & p_{n2c} & p_{n2n1} & p_{n2n2} & p_{n2n3} \\ p_{n3a} & p_{n3b} & p_{n3c} & p_{n3n1} & p_{n3n2} & p_{n3n3} \end{pmatrix}$$

$$p_{ij} = \begin{pmatrix} p_{aa} & p_{ab} & p_{ac} \\ p_{ba} & p_{bb} & p_{bc} \\ p_{ca} & p_{cb} & p_{cc} \end{pmatrix} \qquad p_{in} = \begin{pmatrix} p_{an1} & p_{an2} & p_{an3} \\ p_{bn1} & p_{bn2} & p_{bn3} \\ p_{cn1} & p_{cn2} & p_{cn3} \end{pmatrix}$$

$$p_{nj} = \begin{pmatrix} p_{n1a} & p_{n1b} & p_{n1c} \\ p_{n2a} & p_{n2b} & p_{n2c} \\ p_{n3a} & p_{n3b} & p_{n3c} \end{pmatrix} \qquad p_{nn} = \begin{pmatrix} p_{n1n1} & p_{n1n2} & p_{n1n3} \\ p_{n2n1} & p_{n2n2} & p_{n2n3} \\ p_{n3n1} & p_{n3n2} & p_{n3n3} \end{pmatrix}$$

$$p_{primitive} = \begin{pmatrix} p_{ij} & p_{in} \\ p_{nj} & p_{nn} \end{pmatrix}$$

Potential coefficients in cable is:

$$p_{ii} = 11.17689 \cdot \ln\left(\frac{S_{ii}}{RD_i}\right) \cdot \frac{mile}{\mu F}$$

$$p_{ij} = 11.17689 \cdot \ln\left(\frac{S_{ij}}{D_{ij}}\right) \cdot \frac{mile}{\mu F}$$

where: S_{ii} - distance from conductor i to its image i' [ft]

S_{ij} - distance from conductor i to the image of conductor j [ft]

RD_i - radius of conductor i in [ft]

$$D_{ij} \quad \text{- distance from conducor i to conductor j [ft]}$$

$$P_{abc} = P_{ij} - P_{in} \cdot P_{nn}^{-1} \cdot P_{nj}$$

$$C_{abc} = P_{abc}^{-1}$$

$$Y_{abc} = \left(0 + j \cdot \omega \cdot C_{abc}\right) \cdot \frac{\mu S}{mile} \qquad \omega = 2 \cdot \pi \cdot f$$

<u>Calculation cables capacitance from physical properties</u>

Phase to ground capacitance

$$C_{pg} = \frac{2 \cdot \pi \cdot \varepsilon}{\ln\left(\dfrac{R_b}{RD_c}\right) - \dfrac{1}{k} \cdot \ln\left(\dfrac{k \cdot RD_s}{R_b}\right)}$$

where: $\qquad\qquad \varepsilon = \varepsilon_r \cdot \varepsilon_o$

ε_r - is the relative permittivity of the material (see table below)

$\varepsilon_o := 8.85 \cdot 10^{-12} \dfrac{F}{m}$ is the vacuum permittivity, or

$\varepsilon_o = 0.014243 \dfrac{\mu F}{mile}$

Typical Values of Relative Permittivity (ε_r)

Material	Range of Values of Relative Permittivity
Polyvinyl Chloride (PVC)	3.4–8.0
Ethylene-Propylene Rubber (EPR)	2.5–3.5
Polyethylene (PE)	2.5–2.6
Cross-Linked Polyethlyene (XLPE)	2.3–6.0

Example with previous example data:

$$R_b := 0.0511 \, \text{ft} \qquad R := R_b = 0.613 \, \text{in} \qquad \varepsilon_r := 2.3 \qquad k = 13$$

$$RD_c := \frac{OD_{cond}}{2} = 0.284 \, \text{in}$$

$$RD_s := \frac{d_s}{2} = 0.032 \, \text{in}$$

$$y_{ag} = 0 + j \cdot 2 \cdot \pi \cdot f \cdot C_{pg}$$

$$y_{ag} := \left(0 + 2 \cdot \pi \cdot f \cdot j \cdot \frac{2 \cdot \pi \cdot \varepsilon_r \cdot \varepsilon_o}{\ln\left(\dfrac{R_b}{RD_c}\right) - \dfrac{1}{k} \cdot \ln\left(\dfrac{k \cdot RD_s}{R_b}\right)}\right) = 96.847 j \, \frac{\mu S}{\text{mile}}$$

$$y_{bg} := y_{ag} \qquad y_{cg} := y_{ag}$$

$$Y_{abc} := \begin{pmatrix} y_{ag} & 0 & 0 \\ 0 & y_{bg} & 0 \\ 0 & 0 & y_{cg} \end{pmatrix} = \begin{pmatrix} 96.847j & 0 & 0 \\ 0 & 96.847j & 0 \\ 0 & 0 & 96.847j \end{pmatrix} \frac{\mu S}{\text{mile}}$$

$$Y_{012} := A_s^{-1} \cdot Y_{abc} \cdot A_s$$

$$Y_{012} = \begin{pmatrix} 96.847193j & 0 & 0 \\ 0 & 96.847193j & 0 \\ 0 & 0 & 96.847193j \end{pmatrix} \frac{\mu S}{\text{mile}}$$