

# Cable Systems - Postive/Negative Seq Impedance

## Nomenclature:

<b>GMD</b>	- geometrical mead distance between conductors; depends on construction of the T-line or cable feeder
<b>GMR</b>	- geometric mean radiuis of conductor (single conductor, not bundle);
	values are given in tables with conductor properties

▶ GMR and GMD calculations and Estimations

▶ Conductor Reactance

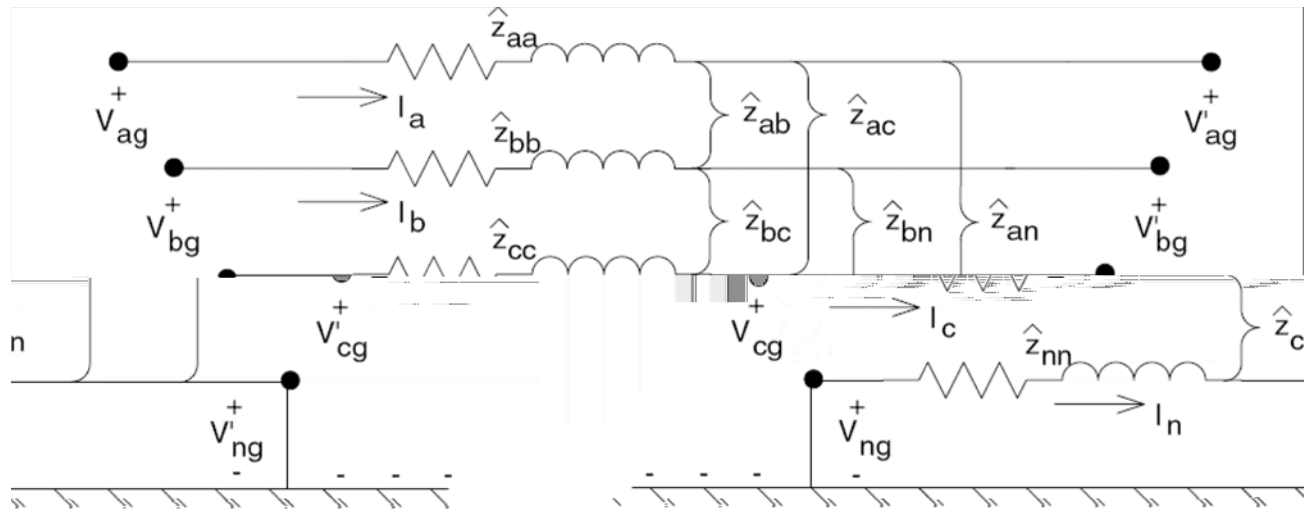
$$z_{\text{primitive}} = \begin{pmatrix} z_{aa} & z_{ab} & z_{ac} & z_{an1} & z_{an2} & z_{an3} \\ z_{ba} & z_{bb} & z_{bc} & z_{bn1} & z_{bn2} & z_{bn3} \\ z_{ca} & z_{cb} & z_{cc} & z_{cn1} & z_{cn2} & z_{cn3} \\ z_{n1a} & z_{n1b} & z_{n1c} & z_{n1n1} & z_{n1n2} & z_{n1n3} \\ z_{n2a} & z_{n2b} & z_{n2c}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

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

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

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

## 3PH, 4W, grounded WYE line segment



$$\begin{pmatrix} V_{sag} \\ V_{sbg} \\ V_{scg} \\ V_{sng} \end{pmatrix} = \begin{pmatrix} V_{rag} \\ V_{rbg} \\ V_{rcg} \\ V_{rng} \end{pmatrix} + \begin{pmatrix} z_{aa} & z_{ab} & z_{ac} & z_{an} \\ z_{ba} & z_{bb} & z_{bc} & z_{bn} \\ z_{ca} & z_{cb} & z_{cc} & z_{cn} \\ z_{na} & z_{nb} & z_{nc} & z_{nn} \end{pmatrix} \begin{pmatrix} I_a \\ I_b \\ I_c \\ I_n \end{pmatrix}$$

$$\begin{pmatrix} V_{sabc} \\ V_{sng} \end{pmatrix} = \begin{pmatrix} V_{rabc} \\ V_{rng} \end{pmatrix} + \begin{pmatrix} z_{ij} & z_{in} \\ z_{nj} & z_{nn} \end{pmatrix} \begin{pmatrix} I_{abc} \\ I_n \end{pmatrix}$$

Because  $V_{sng}$  and  $V_{rng}$  are grounded, then  $V_{sng} = 0$  and  $V_{rng} = 0$

$$V_{sabc} = V_{rabc} + z_{ij} \cdot I_{abc} + z_{in} \cdot I_n$$

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

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

$$V_{sabc} = V_{rabc} + z_{ij} \cdot I_{abc} + z_{in} \cdot (-z_{nn}^{-1} \cdot z_{nj} \cdot I_{abc})$$

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

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

$$V_{s_{abc}} = V_{r_{abc}} + Z_{abc} \cdot I_{abc}$$

Sequence values

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

$$\begin{pmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a_s^2 & a_s \\ 1 & a_s & a_s^2 \end{pmatrix} \cdot \begin{pmatrix} V_{lg0} \\ V_{lg1} \\ V_{lg2} \end{pmatrix}$$

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

$$V_{lg_{abc}} = A_s \cdot V_{lg_{012}}$$

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

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

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

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

$$V_{s_{abc}} = V_{r_{abc}} + Z_{abc} \cdot I_{abc}$$

$$A_s^{-1} \cdot V_{s_{abc}} = A_s^{-1} \cdot V_{r_{abc}} + A_s^{-1} \cdot Z_{abc} \cdot A_s \cdot I_{012}$$

$$V_{lg_{s_{012}}} = V_{lg_{r_{012}}} + Z_{012} \cdot I_{012}$$

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

For symmetrical, transposed line:

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

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

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

Consequently:

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

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

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

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

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

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

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

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

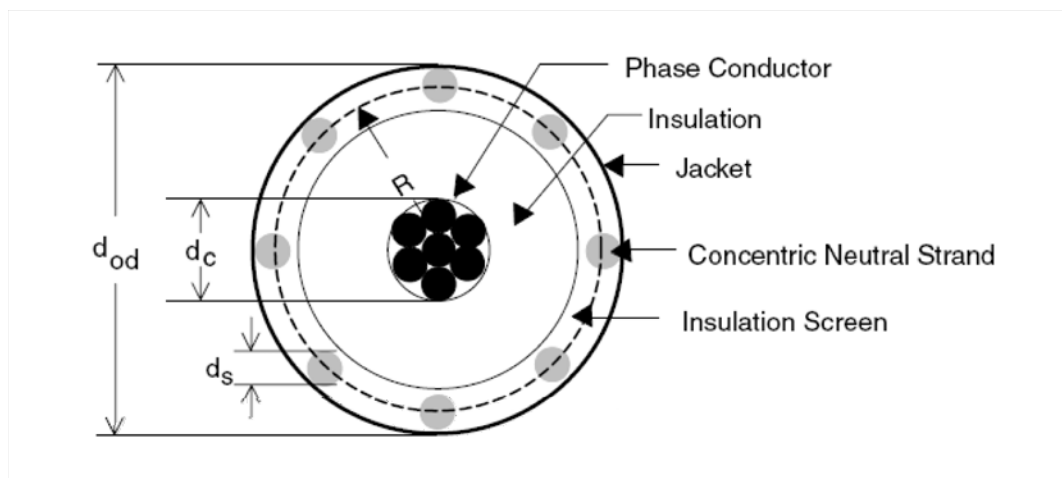
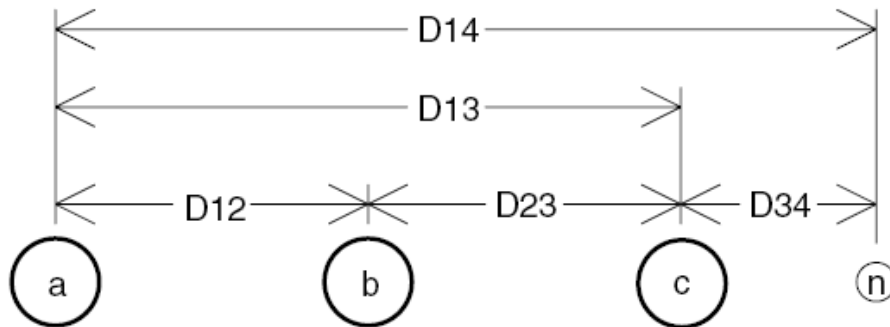
$$z_{in} = 0.0953 + j \cdot 0.12134 \cdot \left( \ln \left( \frac{1}{D_{in}} \right) + 7.93402 \right) \frac{\Omega}{\text{mile}}$$

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

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

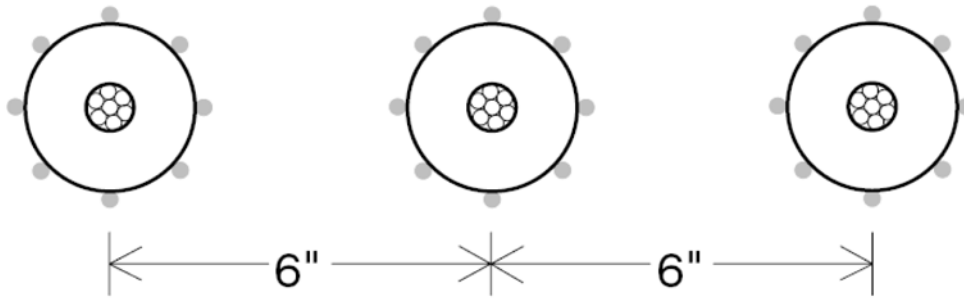
$$z_{11} = z_{22} = r_i + j \cdot 0.12134 \cdot \ln \left( \frac{D_{ij}}{\text{GMR}_i} \right) \cdot \frac{\Omega}{\text{mile}}$$

## 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),  
 $OD_{cab} := 1.29in$ ,  $k := 13$   $f := 60Hz$

For cable: 250 kcmil AA:

$$GMR_{abc} := 0.0171$$

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

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

For neutral strand: #14 Copper

$$GMR_s := 0.00208ft$$

$$d_s := 0.0641in$$

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

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

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

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

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

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

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

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

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

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

$$D_{61} = D_{16} = 1.0\text{-ft} \quad D_{16} := 1$$

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

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

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

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

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

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

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

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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## 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.

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

$$P_{ij} = \begin{pmatrix} P_{aa} & P_{ab} & P_{ac} \\ P_{ba} & P_{bb} & P_{bc} \\ P_{ca} & P_{cb} & P_{cc} \end{pmatrix}$$

$$P_{in} = \begin{pmatrix} P_{an1} & P_{an2} & P_{an3} \\ P_{bn1} & P_{bn2} & P_{bn3} \\ P_{cn1} & P_{cn2} & P_{cn3} \end{pmatrix}$$

$$P_{nj} = \begin{pmatrix} P_{n1a} & P_{n1b} & P_{n1c} \\ P_{n2a} & P_{n2b} & P_{n2c} \\ P_{n3a} & P_{n3b} & P_{n3c} \end{pmatrix}$$

$$P_{nn} = \begin{pmatrix} P_{n1n1} & P_{n1n2} & P_{n1n3} \\ P_{n2n1} & P_{n2n2} & P_{n2n3} \\ P_{n3n1} & P_{n3n2} & P_{n3n3} \end{pmatrix}$$

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

Potential coefficients in cable is:

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

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

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]

$D_{ij}$  - distance from conductor i to conductor j [ft]

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

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

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

## Calculation cables capacitance from physical properties

Phase to ground capacitance

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

where:

$$\epsilon = \epsilon_r \cdot \epsilon_0$$

$\epsilon_r$  - is the relative permittivity of the material (see table below)

$\epsilon_0 := 8.85 \cdot 10^{-12} \frac{F}{m}$  is the vacuum permittivity, or

$$\epsilon_0 = 0.014243 \frac{\mu F}{\text{mile}}$$

### Typical Values of Relative Permittivity ( $\epsilon_r$ )

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 Polyethylene (XLPE)	2.3–6.0

Example with previous example data:

$$R_b := 0.0511\text{ft} \quad R := R_b = 0.613\text{in} \quad \epsilon_r := 2.3 \quad k = 13$$

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

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

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

$$y_{ag} := \left( 0 + 2 \cdot \pi \cdot f \cdot j \cdot \frac{2 \cdot \pi \cdot \epsilon_r \cdot \epsilon_0}{\ln\left(\frac{R_b}{RD_c}\right) - \frac{1}{k} \cdot \ln\left(\frac{k \cdot RD_s}{R_b}\right)} \right) = 96.847j \frac{\mu\text{S}}{\text{mile}}$$

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

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

$$\mathbf{y}_{012} := \mathbf{A}_s^{-1} \cdot \mathbf{y}_{abc} \cdot \mathbf{A}_s$$

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