

Two Source - One line Power System for Fault Analysis

File Name: L23.mcd
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This program computes the directional torque equations for relays R_s and R_r with various faults located at F_1 and F_2 . No zero sequence current can flow from source E_s since Z_s has high zero sequence impedance. Reverse faults are generated by adding impedance between nodes V_1 and V_2 and placing the fault impedance matrix, Z_{f2} .

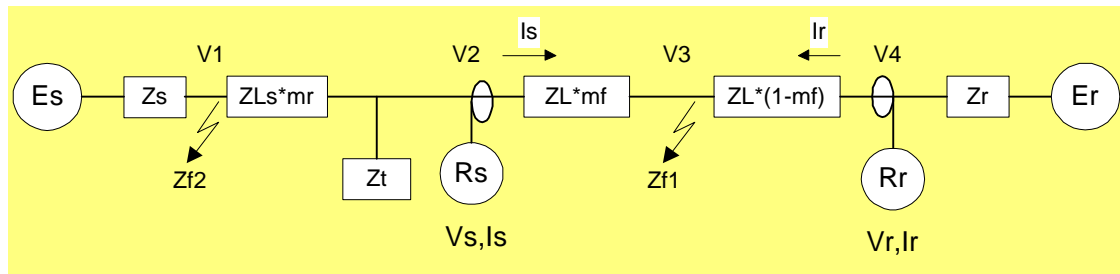


Figure 1. System single line diagram.

1.1. Symmetrical Component Conversions

$$a := e^{2i\frac{\pi}{3}}$$

a = 120 degree phase shift operator
a² = 240 degree phase shift operator

$$A := \left(\frac{1}{3}\right) \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}$$

Phase to Symmetrical Component transformation matrix

$$\text{ZsZm_Z012}(Zs, Zm) := \left. \begin{array}{l} Zabc \leftarrow \begin{pmatrix} Zs & Zm & Zm \\ Zm & Zs & Zm \\ Zm & Zm & Zs \end{pmatrix} \\ Z012 \leftarrow A \cdot Zabc \cdot A^{-1} \\ \text{return } Z012 \end{array} \right|$$

$$\text{Z0Z1_Zabc}(Z0, Z1) := \left. \begin{array}{l} Z012 \leftarrow \begin{pmatrix} Z0 & 0 & 0 \\ 0 & Z1 & 0 \\ 0 & 0 & Z1 \end{pmatrix} \\ Zabc \leftarrow A \cdot Z012 \cdot A^{-1} \\ \text{return } Zabc \end{array} \right|$$

$$\text{Z012_Zabc}(Z012) := \left. \begin{array}{l} Zabc \leftarrow A^{-1} \cdot Z012 \cdot A \\ \text{return } Zabc \end{array} \right|$$

$$\text{Zabc_Z012}(Zabc) := \left. \begin{array}{l} Z012 \leftarrow A \cdot Zabc \cdot A^{-1} \\ \text{return } Z012 \end{array} \right|$$

1.2 Network impedance matrices

1.2.1 Network constants

1.2.2 Transmission line calculations

1.2.1.1 Unbalanced line parameter matrix

$$\text{Line_Length} := 25$$

$$\text{ZL} := \begin{pmatrix} 0.2201 + 0.9608i & 0.1175 + 0.4895i & 0.1133 + 0.4608i \\ 0.1175 + 0.4895i & 0.2285 + 0.9575i & 0.1175 + 0.4895i \\ 0.1133 + 0.4608i & 0.1175 + 0.4895i & 0.2201 + 0.9608i \end{pmatrix} \cdot \text{Line_Length}$$

1.2.2.2 Balanced line parameter computations

$$\text{ZL012} := \text{Zabc_Z012}(\text{ZL})$$

$$\text{ZL0} := \text{ZL012}_{0,0}$$

$$\text{ZL1} := \text{ZL012}_{1,1}$$

$$\text{ZL012} = \begin{pmatrix} 11.377 + 47.989i & 0.131 - 0.197i & -0.236 - 0.015i \\ -0.236 - 0.015i & 2.67 + 11.994i & -0.438 + 0.253i \\ 0.131 - 0.197i & 0.438 + 0.253i & 2.67 + 11.994i \end{pmatrix}$$

1.2.2.3 Set maximum torque angle

$$\text{MTA} := \arg(\text{ZL1})$$

1.2.2.4 Asymmetrical compensation factor

$$k0 := \frac{(\text{ZL0} - \text{ZL1})}{3 \cdot \text{ZL1}}$$

$$k0 = 1.004 - 0.018i$$

$$\text{Ynull} := \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

This matrix is used as a constant for building the system impedance matrix.

1.2.3 Default fault impedance matrices

$$Z_{ff} := \begin{pmatrix} 10^8 & 0 & 0 \\ 0 & 10^8 & 0 \\ 0 & 0 & 10^8 \end{pmatrix}$$

$$Z_{fr} := Z_{ff}$$

1.2.4 S voltage source impedance

Zero sequence admittance Positive sequence admittance Negative sequence admittance

$$Z_{ss0} := (1 + 6i)$$

$$Z_{ss1} := (1 + 6i)$$

$$Z_{ss2} := (1 + 6i)$$

$$Z_{ss012} := \begin{pmatrix} Z_{ss0} & 0 & 0 \\ 0 & Z_{ss1} & 0 \\ 0 & 0 & Z_{ss2} \end{pmatrix}$$

$$Z_{ss} := Z_{012_Zabc}(Z_{ss012})$$

$$Z_{ss} = \begin{pmatrix} 1 + 6i & 0 & 1.057i \times 10^{-15} \\ 0 & 1 + 6i & 0 \\ 0 & 0 & 1 + 6i \end{pmatrix}$$

1.2.6 R voltage source impedance

The R end source has zero sequence impedance equal to the positive sequence impedance.

$$Z_{rr} := \begin{pmatrix} 1 + 6i & 0 & 0 \\ 0 & 1 + 6i & 0 \\ 0 & 0 & 1 + 6i \end{pmatrix}$$

$$Z_{abc_Z012}(Z_{rr}) = \begin{pmatrix} 1 + 6i & 0 & 0 \\ 0 & 1 + 6i & 0 \\ 0 & 0 & 1 + 6i \end{pmatrix}$$

1.3 Voltage sources

1.3.1 Generator constants

Voltage Generator Voltage Power system angle

$$V_g := \frac{120}{\sqrt{3}}$$

$$\text{ang} := 20$$

Specify power angle in degrees -
positive for leading and
negative for lagging,

VT and CT Ratios

$$VTR := 1 \quad TR := 1$$

Power angle shift operator

$$\delta := \cos\left(\frac{\pi \cdot \text{ang}}{180}\right) + \sin\left(\frac{\pi \cdot \text{ang}}{180}\right)i$$

1.3.2 S end voltage source

$$E_s := \begin{pmatrix} V_g \\ V_g \cdot a^2 \\ V_g \cdot a \end{pmatrix}$$

1.3.3 R end voltage source

$$E_r := \begin{pmatrix} V_g \cdot \delta \\ V_g \cdot \delta \cdot a^2 \\ V_g \cdot \delta \cdot a \end{pmatrix}$$

1.4 Subroutines

1.4.1 System Impedance matrix

1.4.1.1 Impedance matrix description

Notes:

1. [3X3] matrix of complex values
2. Scalar in range 0.0001 to 0.9999

Zsystem Definitions

Output:

Z: System impedance matrix

For this system - the result is a [12X12] matrix of complex variables

Input:

Zs: S end voltage source Impedance matrix¹

Zr: R end voltage source Impedance matrix¹

ZL: Total length line impedance matrix¹

Zff: Forward fault impedance matrix¹

Zfr: Reverse fault impedance matrix¹

mf: Percent of line length to forward²

mr: Percent of line length to reverse fault²

1.4.1.2 System Impedance matrix subroutine

Zsystem(Zs,Zr,ZL,Zff,Zfr,mf,mr) :=

$$Y_{11} \leftarrow Z_s^{-1} + Z_{fr}^{-1} + (mr \cdot Z_L)^{-1}$$

$$Y_{12} \leftarrow -(mr \cdot Z_L)^{-1}$$

$$Y_{13} \leftarrow Y_{null}$$

$$Y_{14} \leftarrow Y_{null}$$

$$Y_{21} \leftarrow Y_{12}$$

$$Y_{22} \leftarrow \left[(mf \cdot Z_L)^{-1} + (mr \cdot Z_L)^{-1} \right]$$

$$Y23 \leftarrow -(mf \cdot ZL)^{-1}$$

$$Y24 \leftarrow Y_{\text{null}}$$

$$Y31 \leftarrow Y13$$

$$Y32 \leftarrow Y23$$

$$Y33 \leftarrow \left[(mf \cdot ZL)^{-1} + [(1 - mf) \cdot ZL]^{-1} + Z_{\text{ff}}^{-1} \right]$$

$$Y34 \leftarrow -[(1 - mf) \cdot ZL]^{-1}$$

$$Y41 \leftarrow Y14$$

$$Y42 \leftarrow Y24$$

$$Y43 \leftarrow Y34$$

$$Y44 \leftarrow \left[[(1 - mf) \cdot ZL]^{-1} + Z_{\text{r}}^{-1} \right]$$

$$Y1 \leftarrow \text{stack}(Y11, Y21)$$

$$Y1 \leftarrow \text{stack}(Y1, Y31)$$

$$Y1 \leftarrow \text{stack}(Y1, Y41)$$

$$Y2 \leftarrow \text{stack}(Y12, Y22)$$

$$Y2 \leftarrow \text{stack}(Y2, Y32)$$

$$Y2 \leftarrow \text{stack}(Y2, Y42)$$

$$Y3 \leftarrow \text{stack}(Y13, Y23)$$

$$Y3 \leftarrow \text{stack}(Y3, Y33)$$

$$Y3 \leftarrow \text{stack}(Y3, Y43)$$

```
Y3 ← stack(Y3, Y43)
Y4 ← stack(Y14, Y24)
Y4 ← stack(Y4, Y34)
Y4 ← stack(Y4, Y44)
Y ← augment(Y1, Y2)
Y ← augment(Y, Y3)
Y ← augment(Y, Y4)
return Y-1
```

1.4.2 Compute system node voltages

Solve_Node_Voltages Definitions

Output:

Vn: Vnode voltages¹

Input:

Es: S end voltage source²

Er: R end voltage source²

Zs: S end voltage source Impedance matrix³

Zr: R end voltage source Impedance matrix³

ZL: Total length line impedance matrix³

Zff: Forward fault impedance matrix³

Zfr: Reverse fault impedance matrix³

mf: Percent of line length to forward⁴

mr: Percent of line length to reverse fault⁴

Notes:

1. [1X12] column vector = [V1 : V2 : V3 : V4]^T
2. [1X3] column vector
3. [3X3] matrix of complex values
4. Scalar in range 0.0001 to 0.9999

```
Solve_Node_Voltages(Es ,Er ,Zs ,Zr ,ZL ,Zff ,Zfr ,mf ,mr) :=  
Z ← Zsystem(Zs ,Zr ,ZL ,Zff ,Zfr ,mf ,mr)  
NullSrc ← ( 0 0 0 )T  
Igen ← Zs-1 · Es  
Igen ← stack(Igen ,NullSrc)  
Igen ← stack(Igen ,NullSrc)  
Igen ← stack[ Igen , ( Zr-1 · Er ) ]  
V ← Z · Igen  
return V
```

1.4.3 Compute relay currents

Solve_currents Definitions

Output:

Ib: Branch currents¹

IS - Send relay current

IR - R end relay currents

Input:

V: Node voltage vector computed by

Solve_Node_Voltages²

ZL: Total length line impedance matrix³

mf: Percent of line length to forward⁴

Notes:

1. 1X9 Column vector = [IS : IR]^T

2. [1X12] column vector = [V1 : V2 : V3 : V4]^T

3. 3X3 matrix of complex values

4. Scalar in range 0.0001 to 0.9999

```

Solve_currents(V,ZL,mf) :=
  Is ← (mf·ZL)-1·(submatrix(V,3,5,0,0) – submatrix(V,6,8,0,0))
  Ir ← [(1 – mf)·ZL]-1·(submatrix(V,9,11,0,0) – submatrix(V,6,8,0,0))
  Ib ← Is
  Ib ← stack(Ib,Ir)
  return Ib

```

1.4.4 Rectangular to polar conversion

```

rect2polar(R) :=
  for i ∈ 0..2
    m ← |Ri|
    α ← arg(Ri)· $\frac{180}{\pi}$ 
    p ← ( m α )
    Pol ← p if i < 1
    Pol ← stack(Pol,p) if i > 0
  return Pol

```

Rectangular to polar coordinate conversion

Output: [V or I : Angle]¹

Input: [V or I complex variables]²

Notes:

1.3X2 matrix of scalar values

2.[3X1] vector of complex variables

1.5 Calculate prefault voltages and currents

The first calculation is for an unfaulted system. The locations of the forward (mf) and reverse (mr) faults doesn't matter at this point because the fault matrix represents essentially and open circuit. "Vprevault" is a matrix of node voltages for the prefault condition "Ibr" extracts the three phase Relay S and R currents as well as the total three phase forward fault current. "VSabc", "VRabc", and "VFabc" are 1x3 column vectors for the voltages seen by Relay s, Relay R and at the forward fault.

Location of forward fault $mf := 0.5$

Location of reverse fault $mr := 0.5$

The values of mf and mr are not important for the pre-fault analysis and the fault matrices are infinite

Compute node voltages

$V_{prefault} := \text{Solve_Node_Voltages}(Es, Er, Z_{ss}, Z_{rr}, Z_L, Z_{ff}, Z_{fr}, mf, mr)$

Extract Relay voltages

$VS_{abc_prefault} := \text{submatrix}(V_{prefault}, 3, 5, 0, 0)$

$VR_{abc_prefault} := \text{submatrix}(V_{prefault}, 6, 8, 0, 0)$

$VS_{012} := A \cdot VS_{abc_prefault}$

$VR_{012} := A \cdot VR_{abc_prefault}$

$VS_{1pol} := VS_{012_1}$

$VR_{1pol} := VR_{012_1}$

Display Relay and fault voltages in polar notation

$$\text{rect2polar}(VS_{abc_prefault}) = \begin{pmatrix} 68.187 & 7.951 \\ 68.209 & -112.002 \\ 68.265 & 127.965 \end{pmatrix}$$

$$\text{rect2polar}(VR_{abc_prefault}) = \begin{pmatrix} 68.359 & 12.044 \\ 68.334 & -108.001 \\ 68.28 & 132.035 \end{pmatrix}$$

$$\text{rect2polar}(VS_{012}) = \begin{pmatrix} 6.728 \times 10^{-3} & 148.55 \\ 68.22 & 7.971 \\ 0.04 & -126.877 \end{pmatrix}$$

$$\text{rect2polar}(VR_{012}) = \begin{pmatrix} 6.728 \times 10^{-3} & -31.45 \\ 68.324 & 12.026 \\ 0.04 & 53.123 \end{pmatrix}$$

Extract Relay and fault currents

Extract Relay and fault currents

```
Ibr := Solve_currents(Vprefault,ZL,mf)
```

```
ISprefault := submatrix(Ibr,0,2,0,0)
```

```
IRprefault := submatrix(Ibr,3,5,0,0)
```

Display Relay and fault currents in polar notation

$$\text{rect2polar}(\text{ISprefault}) = \begin{pmatrix} 0.777 & -157.403 \\ 0.803 & 81.661 \\ 0.782 & -40.255 \end{pmatrix}$$

$$\text{rect2polar}(\text{IRprefault}) = \begin{pmatrix} 0.777 & 22.597 \\ 0.803 & -98.339 \\ 0.782 & 139.745 \end{pmatrix}$$

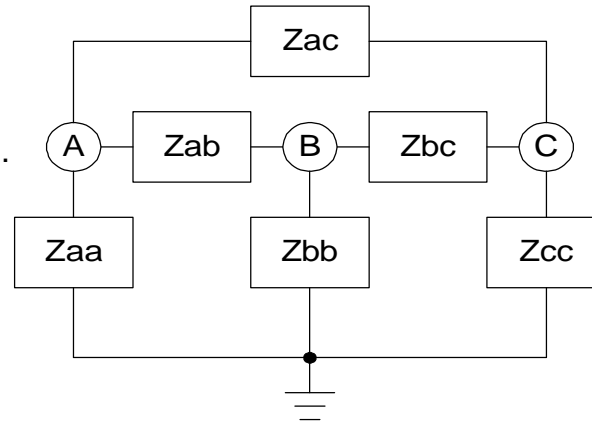
1.6 Calculate prefault voltages and currents

The second calculation is for an faulted system. The locations of the forward is established by setting the value of mf as a decimal fraction of the total line length. If mf equalt 0.25, then the fault is located 0.25 * the line length from Relay S toward Relay R. Line impedance is added to the source impedance by adjusting the value of mr shown as ZLs in Figure 1. The amount of impedance added is determined by Zls = mr*ZL where ZL is the system line impedance. This allows faults to be placed behind Relay S but still forward of relay R. Use small nonzero positive values (0.0001) for mr to add no additional impedance to the source impedance.

```
r := 0.8 Relay reach
```

The parameters associated with the forward and reverse fault matrix are illustrated in Figure 2. Use impedance values of 10^6 for open circuits. Phase to phase faults are generated by setting Z_{ab} , Z_{bc} , and / or Z_{ac} to small values. Phase to ground faults are generated by setting Z_{aa} , Z_{bb} , and / or Z_{cc} to small values. The minimum fault impedance should be limited to 0.0001. Fault impedances can be complex. Not specifying a fault impedance defaults to an open circuit fault matrix. Changing the left hand variable from Z_{ff} to Z_{fr} moves the fault matrix to the Z_{f2} position making the fault matrix behind Relay S.

Figure 2. Fault matrix diagram.



$$Z_{aa} := 10^6$$

$$Z_{bb} := 10^{-6}$$

$$Z_{cc} := 10^6$$

$$Z_{ab} := 10^6$$

$$Z_{bc} := 10^6$$

$$Z_{ac} := 10^{-6}$$

$$Z_f := \begin{bmatrix} (Z_{aa}^{-1} + Z_{ab}^{-1} + Z_{ac}^{-1}) & -Z_{ab}^{-1} & -Z_{ac}^{-1} \\ -Z_{ab}^{-1} & (Z_{bb}^{-1} + Z_{ab}^{-1} + Z_{bc}^{-1}) & -Z_{bc}^{-1} \\ -Z_{ac}^{-1} & -Z_{bc}^{-1} & (Z_{cc}^{-1} + Z_{ac}^{-1} + Z_{bc}^{-1}) \end{bmatrix}^{-1}$$

$$Z_{fr} := Z_f$$

Change the assignment variable from "Zff" to "Zfr" for reverse faults

1.7 Compute relay voltages and currents for the faulted system

Location of forward fault $mf := 0.15$ Reverse fault location $mr := 0.0001$

$Vnode := \text{Solve_Node_Voltages}(Es, Er, Zss, Zrr, ZL, Zff, Zfr, mf, mr)$

1.7.1 Extract Relay and fault voltages

$VSabc := \text{submatrix}(Vnode, 3, 5, 0, 0)$

$VRabc := \text{submatrix}(Vnode, 9, 11, 0, 0)$

$VS012 := A \cdot VSabc$
 $VR012 := A \cdot VRabc$

$VS0pol := VS012_0$

$VR0pol := VR012_0$

$VS2pol := VS012_2$

$VR2pol := VR012_2$

Display Relay and fault voltages in polar notation

$$\text{rect2polar}(VSabc) = \begin{pmatrix} 38.595 & 65.211 \\ 5.168 \times 10^{-3} & -102.753 \\ 38.593 & 65.223 \end{pmatrix}$$

$$\text{rect2polar}(VRabc) = \begin{pmatrix} 51.742 & 24.466 \\ 51.687 & -102.598 \\ 49.223 & 131.757 \end{pmatrix}$$

1.7.2 Extract Relay and polarizing currents

```
Ibr := Solve_currents(Vnode,ZL,mf)
```

```
ISabc := submatrix(Ibr,0,2,0,0)
```

```
IRabc := submatrix(Ibr,3,5,0,0)
```

```
IS012 := A·ISabc
```

```
IR012 := A·IRabc
```

```
IS0pol := IS0120
```

```
IR0pol := IR0120
```

```
IS2pol := IS0122
```

```
IR2pol := IR0122
```

Display Relay and fault currents in polar notation

$$\text{rect2polar}(\text{ISabc}) = \begin{pmatrix} 2.984 & 106.637 \\ 2.927 & 7.024 \\ 3.575 & -101.599 \end{pmatrix}$$

$$\text{rect2polar}(\text{IRabc}) = \begin{pmatrix} 2.984 & -73.363 \\ 2.927 & -172.976 \\ 3.575 & 78.401 \end{pmatrix}$$

1.7.4 Compute symmetrical component polarizing torque directional values

1.7.4.1 Display voltage and current symmetrical components at Relay S and R

Calculations for these values are completed in Section 1.7.1 and 1.7.2

$$\text{rect2polar}(VS012) = \begin{pmatrix} 25.728 & 65.216 \\ 12.869 & 5.221 \\ 12.864 & 125.216 \end{pmatrix}$$

$$\text{rect2polar}(VR012) = \begin{pmatrix} 2.761 & 68.46 \\ 50.676 & 17.975 \\ 3.857 & 123.354 \end{pmatrix}$$

$$\text{rect2polar}(IS012) = \begin{pmatrix} 0.454 & -12.078 \\ 3.078 & 124.949 \\ 0.634 & 42.816 \end{pmatrix}$$

$$\text{rect2polar}(IR012) = \begin{pmatrix} 0.454 & 167.922 \\ 3.078 & -55.051 \\ 0.634 & -137.184 \end{pmatrix}$$

$$\text{MTA} = 77.45 \text{ deg}$$

1.7.4.6.1 Relay S zero sequence voltage polarized impedance value

$$Z_{32SV0} := \frac{\left(\operatorname{Re} \left(3 \cdot VS_{012_0} \cdot \left[\left(\frac{Z_{L0}}{|Z_{L0}|} \right) \cdot 3 \cdot IS_{012_0} \right] \right) \right)}{\left(|3 \cdot IS_{012_0}| \right)^2}$$

$$Z_{32SV0} = 56.673$$

1.7.4.6.2 Relay R zero sequence voltage polarized impedance value

$$Z_{32RV0} := \frac{\left[\operatorname{Re} \left[\left(VR_{012_0} \right) \cdot \left[\left(\frac{Z_{L0}}{|Z_{L0}|} \right) \cdot IR_{012_0} \right] \right] \right]}{\left(|IR_{012_0}| \right)^2}$$

$$Z_{32RV0} = -6.069$$

1.7.4.6.3 Relay S negative sequence voltage polarized torque value

$$Z_{32SV2} := \frac{\left(\operatorname{Re} \left(VS_{012_2} \cdot \left[\left(\frac{Z_{L1}}{|Z_{L1}|} \right) \cdot IS_{012_2} \right] \right) \right)}{\left(|IS_{012_2}| \right)^2}$$

$$Z_{32SV2} = 20.214$$

1.7.4.6.4 Relay R negative sequence voltage polarized torque value

$$Z_{32RV2} := \frac{\left[\operatorname{Re} \left[\left(VR_{012_2} \right) \cdot \left[\left(\frac{Z_{L1}}{|Z_{L1}|} \right) \cdot IR_{012_2} \right] \right] \right]}{\left(|IR_{012_2}| \right)^2}$$

$$Z_{32RV2} = -6.074$$

1.8 Distance element polarized by prefault positive sequence voltage

1.8.1 Sending end polarizing

$$VS_{a1} := \frac{[VS_{abc_prefault_0} + a \cdot VS_{abc_prefault_1} - (a + 1) \cdot VS_{abc_prefault_2}]}{3}$$

$$VS_{b1} := \frac{[VS_{abc_prefault_1} + a \cdot VS_{abc_prefault_2} - (a + 1) \cdot VS_{abc_prefault_0}]}{3}$$

$$VS_{c1} := \frac{[VS_{abc_prefault_2} + a \cdot VS_{abc_prefault_0} - (a + 1) \cdot VS_{abc_prefault_1}]}{3}$$

1.8.2 Receiving end polarizing

$$VR_{a1} := \frac{[VR_{abc_prefault_0} + a \cdot VR_{abc_prefault_1} - (a + 1) \cdot VR_{abc_prefault_2}]}{3}$$

$$VR_{b1} := \frac{[VR_{abc_prefault_1} + a \cdot VR_{abc_prefault_2} - (a + 1) \cdot VR_{abc_prefault_0}]}{3}$$

$$VR_{c1} := \frac{[VR_{abc_prefault_2} + a \cdot VR_{abc_prefault_0} - (a + 1) \cdot VR_{abc_prefault_1}]}{3}$$

1.8.3 Sending end reach

1.8.4 Receiving end reach

Ground Elements

$$msag := \frac{\operatorname{Re}\left(VSabc_0 \cdot \overline{VSa1}\right)}{\operatorname{Re}\left[\left[ZL1 \cdot \left(ISabc_0 + 3 \cdot k0 \cdot IS012_0\right) \cdot \overline{VSa1}\right]\right]}$$

$$mrag := \frac{\operatorname{Re}\left VRabc_0 \cdot \overline{VRa1}\right)}{\operatorname{Re}\left[\left[ZL1 \cdot \left(IRabc_0 + 3 \cdot k0 \cdot IR012_0\right) \cdot \overline{VRa1}\right]\right]}$$

$$msbg := \frac{\operatorname{Re}\left(VSabc_1 \cdot \overline{VSb1}\right)}{\operatorname{Re}\left[\left[ZL1 \cdot \left(ISabc_1 + 3 \cdot k0 \cdot IS012_0\right) \cdot \overline{VSb1}\right]\right]}$$

$$mrbg := \frac{\operatorname{Re}\left VRabc_1 \cdot \overline{VRb1}\right)}{\operatorname{Re}\left[\left[ZL1 \cdot \left(IRabc_1 + 3 \cdot k0 \cdot IR012_0\right) \cdot \overline{VRb1}\right]\right]}$$

$$mscg := \frac{\operatorname{Re}\left(VSabc_2 \cdot \overline{VSc1}\right)}{\operatorname{Re}\left[\left[ZL1 \cdot \left(ISabc_2 + 3 \cdot k0 \cdot IS012_0\right) \cdot \overline{VSc1}\right]\right]}$$

$$mrcg := \frac{\operatorname{Re}\left VRabc_2 \cdot \overline{VRc1}\right)}{\operatorname{Re}\left[\left[ZL1 \cdot \left(IRabc_2 + 3 \cdot k0 \cdot IR012_0\right) \cdot \overline{VRc1}\right]\right]}$$

Phase Elements

$$msab := \frac{\operatorname{Re}\left[\left(VSabc_0 - VSabc_1\right) \cdot \left(\overline{-i \cdot VSc1}\right)\right]}{\operatorname{Re}\left[\left[ZL1 \cdot \left(ISabc_0 - ISabc_1\right) \cdot \left(\overline{-i \cdot VSc1}\right)\right]\right]}$$

$$mrab := \frac{\operatorname{Re}\left[\left VRabc_0 - VRabc_1\right) \cdot \left(\overline{-i \cdot VRc1}\right)\right]}{\operatorname{Re}\left[\left[ZL1 \cdot \left(IRabc_0 - IRabc_1\right) \cdot \left(\overline{-i \cdot VRc1}\right)\right]\right]}$$

$$msbc := \frac{\operatorname{Re}\left[\left(VSabc_1 - VSabc_2\right) \cdot \left(\overline{-i \cdot VSa1}\right)\right]}{\operatorname{Re}\left[\left[ZL1 \cdot \left(ISabc_1 - ISabc_2\right) \cdot \left(\overline{-i \cdot VSa1}\right)\right]\right]}$$

$$mrbc := \frac{\operatorname{Re}\left[\left VRabc_1 - VRabc_2\right) \cdot \left(\overline{-i \cdot VRa1}\right)\right]}{\operatorname{Re}\left[\left[ZL1 \cdot \left(IRabc_1 - IRabc_2\right) \cdot \left(\overline{-i \cdot VRa1}\right)\right]\right]}$$

$$msca := \frac{\operatorname{Re}\left[\left(VSabc_2 - VSabc_0\right) \cdot \left(\overline{-i \cdot VSb1}\right)\right]}{\operatorname{Re}\left[\left[ZL1 \cdot \left(ISabc_2 - ISabc_0\right) \cdot \left(\overline{-i \cdot VSb1}\right)\right]\right]}$$

$$mrca := \frac{\operatorname{Re}\left[\left VRabc_2 - VRabc_0\right) \cdot \left(\overline{-i \cdot VRb1}\right)\right]}{\operatorname{Re}\left[\left[ZL1 \cdot \left(IRabc_2 - IRabc_0\right) \cdot \left(\overline{-i \cdot VRb1}\right)\right]\right]}$$

$$\text{msag} = -0.766$$

$$\text{msbg} = -9.95 \times 10^{-5}$$

$$\text{mscg} = -0.563$$

$$\text{msab} = -0.622$$

$$\text{msbc} = -0.557$$

$$\text{msca} = -1.039 \times 10^{-4}$$

$$\text{mrag} = 1.941$$

$$\text{mrbg} = 0.994$$

$$\text{mrcg} = 1.456$$

$$\text{mrab} = 1.65$$

$$\text{mrbc} = 1.49$$

$$\text{mrca} = 1.039$$