Series Fault Examples

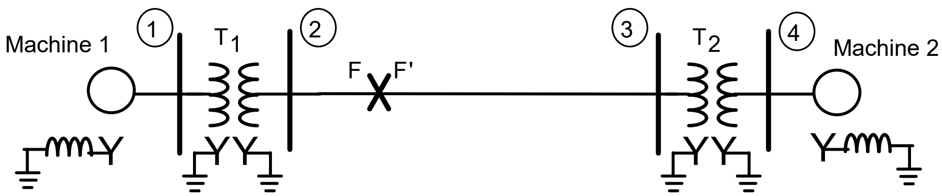
$pu := 1$ $MVA := 1000kW$

$a := 1e^{j \cdot 120deg}$ $A_{012} := \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix}$

Single Phase Open Examples

Example 1:

- System one-line diagram:



Machines 1 and 2: $S_{Mach} := 100MVA$ $V_{machine} := 20kV$

$X_{dMach''} := 20\%$ $X_{1Mach} := X_{dMach''}$ $X_{2Mach} := X_{1Mach}$

$X_{0Mach} := 4\%$ $X_{nMach} := 5\%$

Transformers T1 and T2: $S_{Tran} := 1000MVA$ $V_{HV} := 345kV$ $V_{LV} := 20kV$ $X_T := 8\%$

Transmission Line $X_{L1} := 15\%$ $X_{L2} := X_{L1}$ $X_{L0} := 50\%$

$S_{Base} := 100MVA$

$V_{BLine} := 345kV \qquad V_{B\_mach} := V_{BLine} \cdot \left(\frac{V_{LV}}{V_{HV}}\right) \qquad V_{B\_mach} = 20 \cdot kV$

No change of base calculations are needed for this system.

Determine internal source voltages:

$magS_{pre} := 80MVA \qquad pf_{pre} := 0.85 \text{ lagging} \qquad \theta_{pre} := acos(pf_{pre}) \qquad \theta_{pre} = 31.79 \cdot deg$

$S_{pre} := \frac{magS_{pre}}{S_{Base}} \cdot e^{j \cdot \theta_{pre}} \qquad S_{pre} = (0.68 + 0.42i) \cdot pu \qquad \left|S_{pre}\right| = 0.8 \cdot pu$

Assume bus 3 voltage is 1.0 pu at and angle of 0 degrees.

$V_3 := 1.0$

$I_{load} := \overline{\left(\frac{S_{pre}}{V_3}\right)} \qquad I_{load} = 0.68 - 0.42i \qquad \left|I_{load}\right| = 0.8 \cdot pu \qquad arg(I_{load}) = -31.79 \cdot deg$

Internal voltage on the motor (since we don't know steady-state synchronous reactance, use X1):

$E_2 := V_3 - I_{load} \cdot j(X_T + X_{1Mach}) \qquad \left|E_2\right| = 0.9 \qquad \phi_2 := arg(E_2) \qquad \phi_2 = -12.18 \cdot deg$

Generator internal voltage:

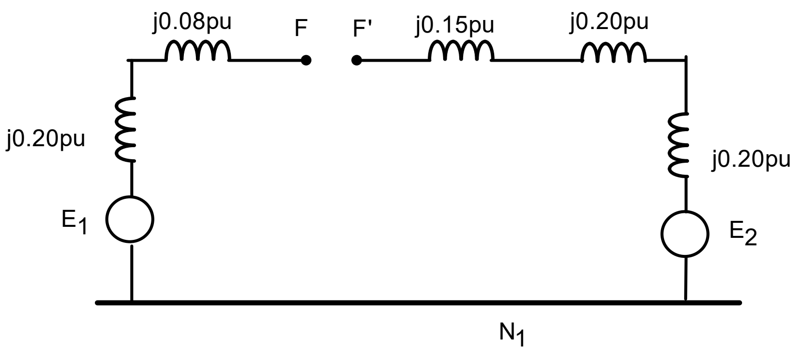
$E_1 := V_3 + I_{load} \cdot (j \cdot X_{L1} + j \cdot X_T + j \cdot X_{1Mach}) \qquad \left|E_1\right| = 1.22 \cdot pu \qquad \phi_1 := arg(E_1) \qquad \phi_1 = 13.9 \cdot deg$

Check result by calculating power transfer between sources and current:

$$P_{trans} := \frac{|E_1|\cdot|E_2|\cdot\sin(\phi_1-\phi_2)}{2\cdot X_{1Mach}+2\cdot X_T+X_{L1}} \qquad P_{trans}-\mathrm{Re}(S_{pre}) = 0$$

$$I_{trans} := \frac{E_1-E_2}{j(2\cdot X_{1Mach}+2\cdot X_T+X_{L1})} \qquad I_{trans}-I_{load} = 0$$

- Positive sequence equivalent circuit (with phase open point indicated).



Find total impedance counterclockwise around loop from F to F'

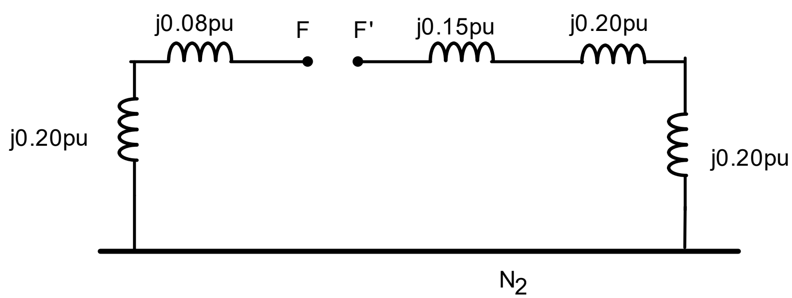
$$Z_{1total} := j\cdot(X_{1Mach}+X_T+X_{L1}+X_T+X_{1Mach})$$

$$Z_{1total} = 0.71i\cdot pu$$

$$Z_{1FF'} := Z_{1total}$$

$$V_{equiv} := E_1 - E_2$$

- Negative sequence equivalent circuit:



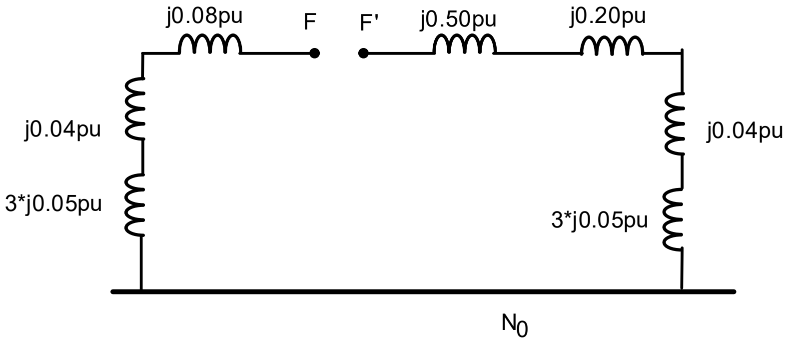
Find total impedance counterclockwise around loop from F to F'

$$Z_{2total} := j\cdot(X_{2Mach}+X_T+X_{L2}+X_T+X_{2Mach})$$

$$Z_{2total} = 0.71i\cdot pu$$

$$Z_{2FF'} := Z_{2total}$$

- Zero sequence equivalent:



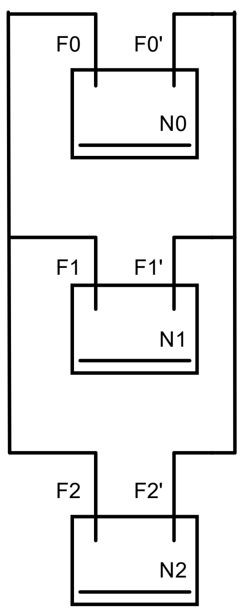
Find total impedance counterclockwise around loop from F to F'

$$Z_{0total} := j\cdot\left(2\cdot X_{0Mach} + 2\cdot X_T + X_{L0} + 2\cdot 3\cdot X_{nMach}\right)$$

$$Z_{0total} = 1.04i\cdot pu$$

$$Z_{0FF'} := Z_{0total}$$

Now solve for the single phase open circuit currents and voltages:



$$I_1 := \frac{V_{equiv}}{Z_{1FF'} + \left(\frac{1}{Z_{2FF'}} + \frac{1}{Z_{0FF'}}\right)^{-1}}$$

$$I_1 = (0.43 - 0.26i)\cdot pu$$

$$\left|I_1\right| = 0.5\cdot pu \qquad \arg\left(I_1\right) = -31.79\cdot deg$$

$$I_2 := -I_1\cdot\left(\frac{Z_{0FF'}}{Z_{2FF'} + Z_{0FF'}}\right)$$

$$I_2 = (-0.25 + 0.16i)\cdot pu$$

$$\left|I_2\right| = 0.3\cdot pu \qquad \arg\left(I_2\right) = 148.21\cdot deg$$

$$I_0 := -I_1\cdot\left(\frac{Z_{2FF'}}{Z_{2FF'} + Z_{0FF'}}\right)$$

$$I_0 = (-0.17 + 0.11i)\cdot pu$$

$$\left|I_0\right| = 0.2\cdot pu \qquad \arg\left(I_0\right) = 148.21\cdot deg$$

$$I_{abc} := A_{012} \cdot \begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix} \qquad \overrightarrow{\left| I_{abc} \right|} = \begin{pmatrix} 0 \\ 0.76 \\ 0.76 \end{pmatrix} \cdot pu \qquad \arg\left(I_{abc_1}\right) = -145.57 \cdot deg$$

$$\arg\left(I_{abc_2}\right) = 82 \cdot deg$$

Using the right have the sequence equivalent circuits:

$$V_{3new1} := E_2 + I_1 \cdot j \cdot \left(X_{1Mach} + X_T\right) \qquad \left|V_{3new1}\right| = 0.96 \cdot pu \qquad \arg\left(V_{3new1}\right) = -4.25 \cdot deg$$

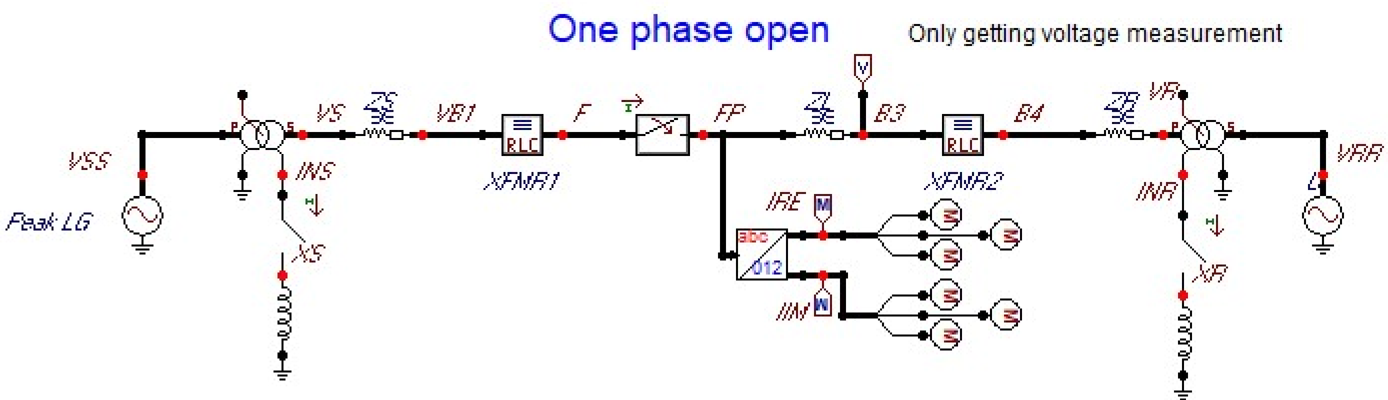
$$V_{3new2} := 0 + I_2 \cdot j \cdot \left(X_{2Mach} + X_T\right) \qquad \left|V_{3new2}\right| = 0.08 \cdot pu \qquad \arg\left(V_{3new2}\right) = -121.79 \cdot deg$$

$$V_{3new0} := 0 + I_0 \cdot j \cdot \left(X_{0Mach} + X_T + 3 \cdot X_{nMach}\right) \qquad \left|V_{3new0}\right| = 0.05 \cdot pu \qquad \arg\left(V_{3new0}\right) = -121.79 \cdot deg$$

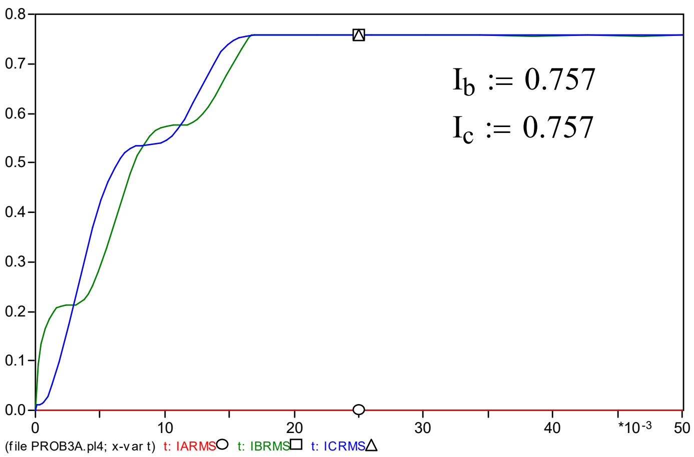
$$V_{3newABC} := A_{012} \cdot \begin{pmatrix} V_{3new0} \\ V_{3new1} \\ V_{3new2} \end{pmatrix} \qquad \overrightarrow{\left|V_{3newABC}\right|} = \begin{pmatrix} 0.903 \\ 0.971 \\ 1.014 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V_{3newABC}\right)} = \begin{pmatrix} -12.06 \\ -119.95 \\ 118.58 \end{pmatrix} \cdot deg$$

$$\Delta V_{ABC} := 1.0 \cdot \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} - V_{3newABC} \qquad \overrightarrow{\left|\Delta V_{ABC}\right|} = \begin{pmatrix} 0.22 \\ 0.03 \\ 0.03 \end{pmatrix} \qquad \overrightarrow{\arg\left(\Delta V_{ABC}\right)} = \begin{pmatrix} 58.21 \\ -121.79 \\ -121.79 \end{pmatrix} \cdot deg$$

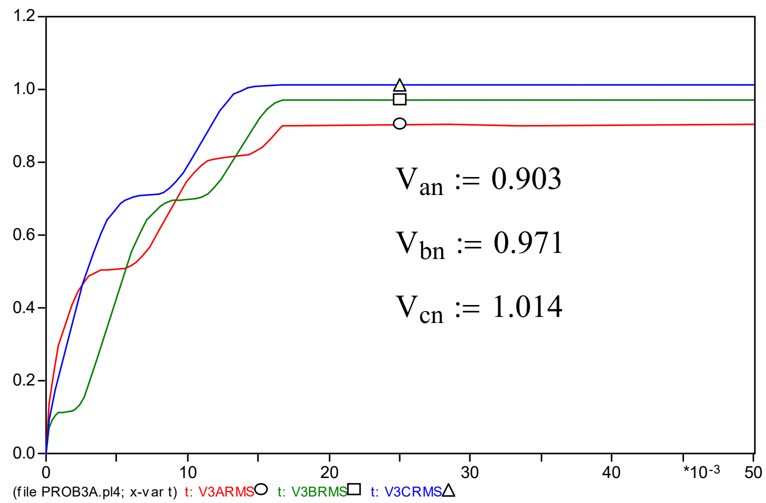
ATP simulation results:



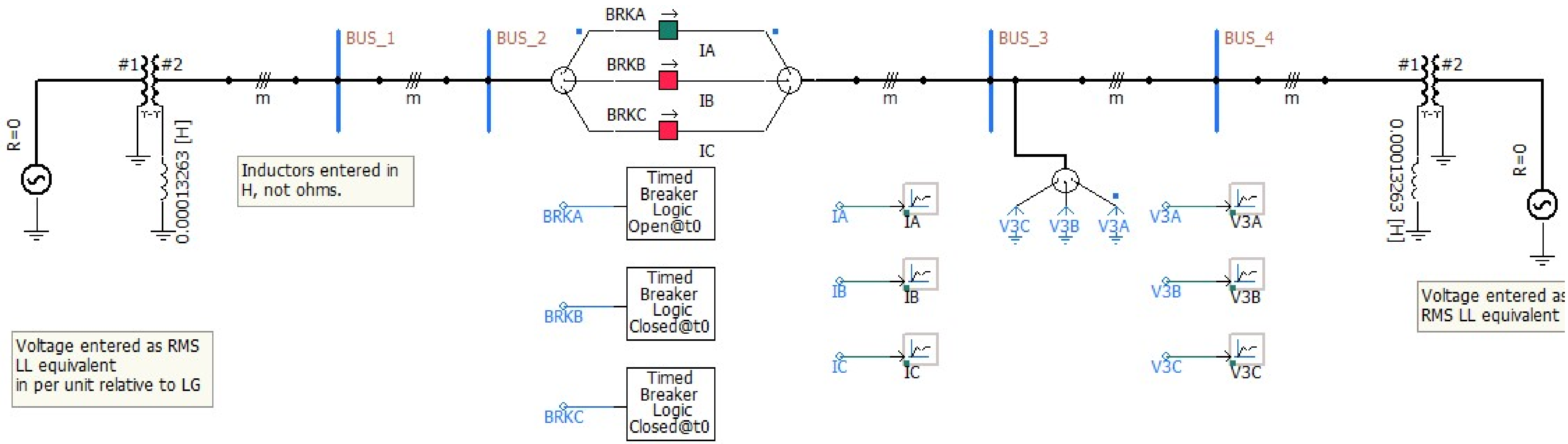
Currents

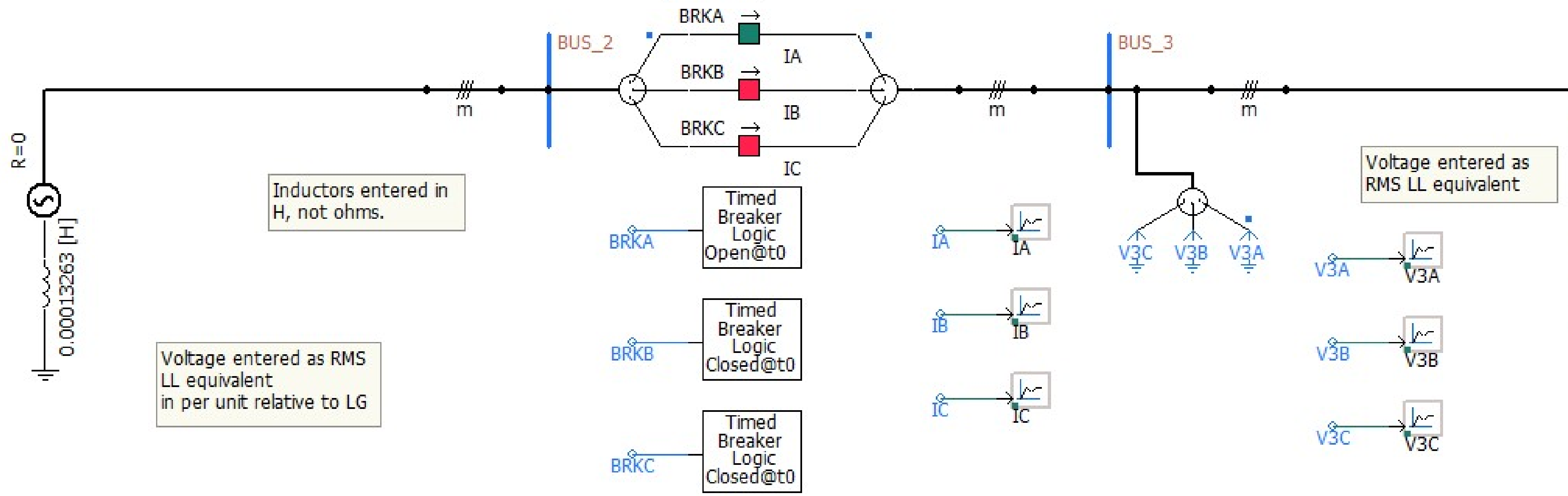


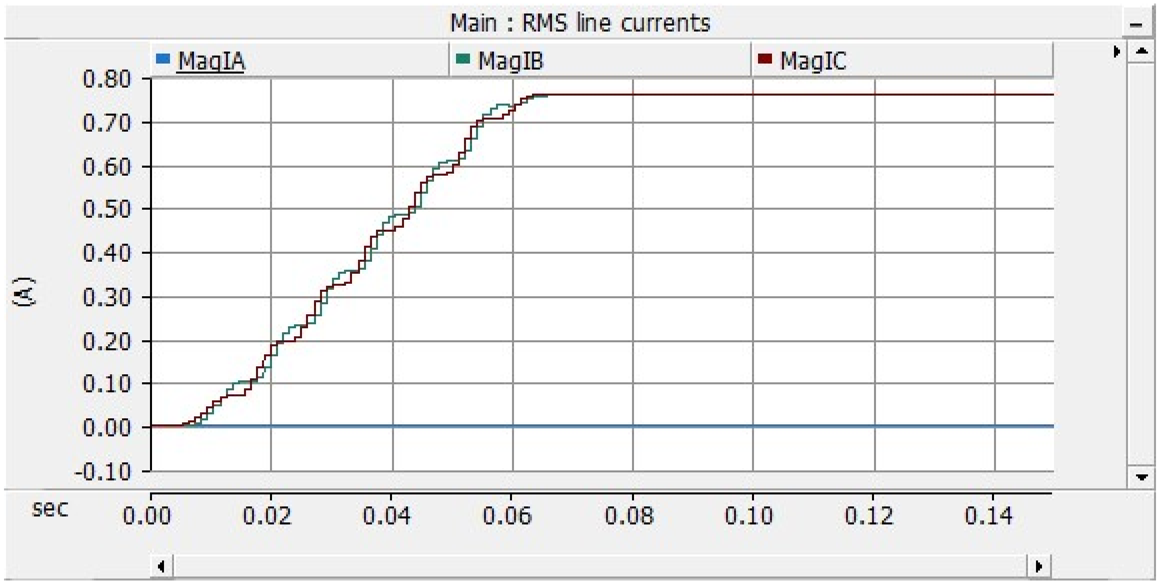
Voltages

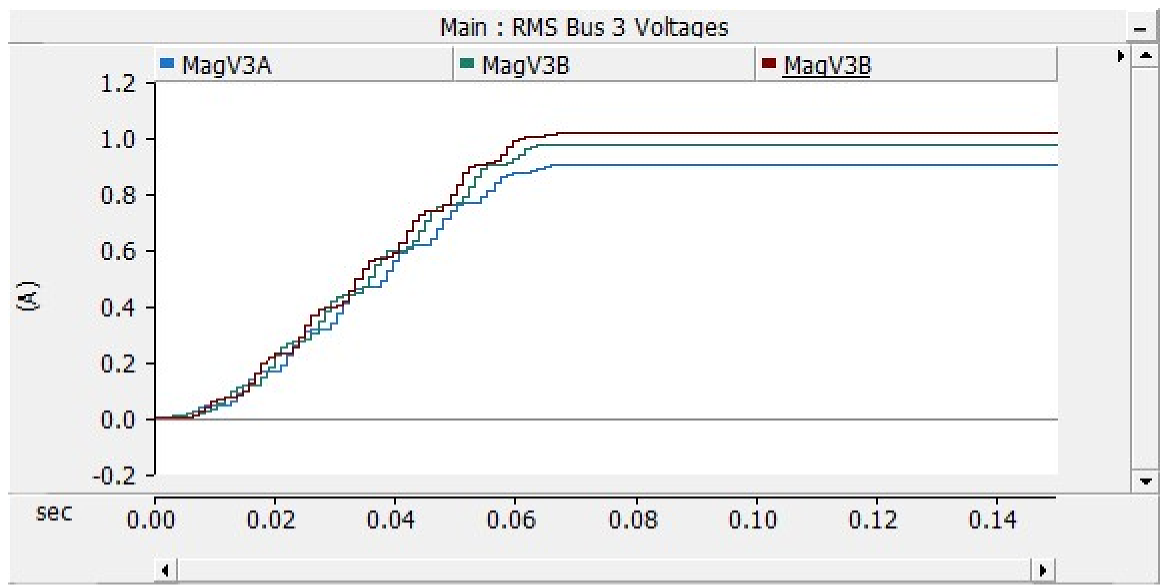


PSCAD/EMTDC implementation

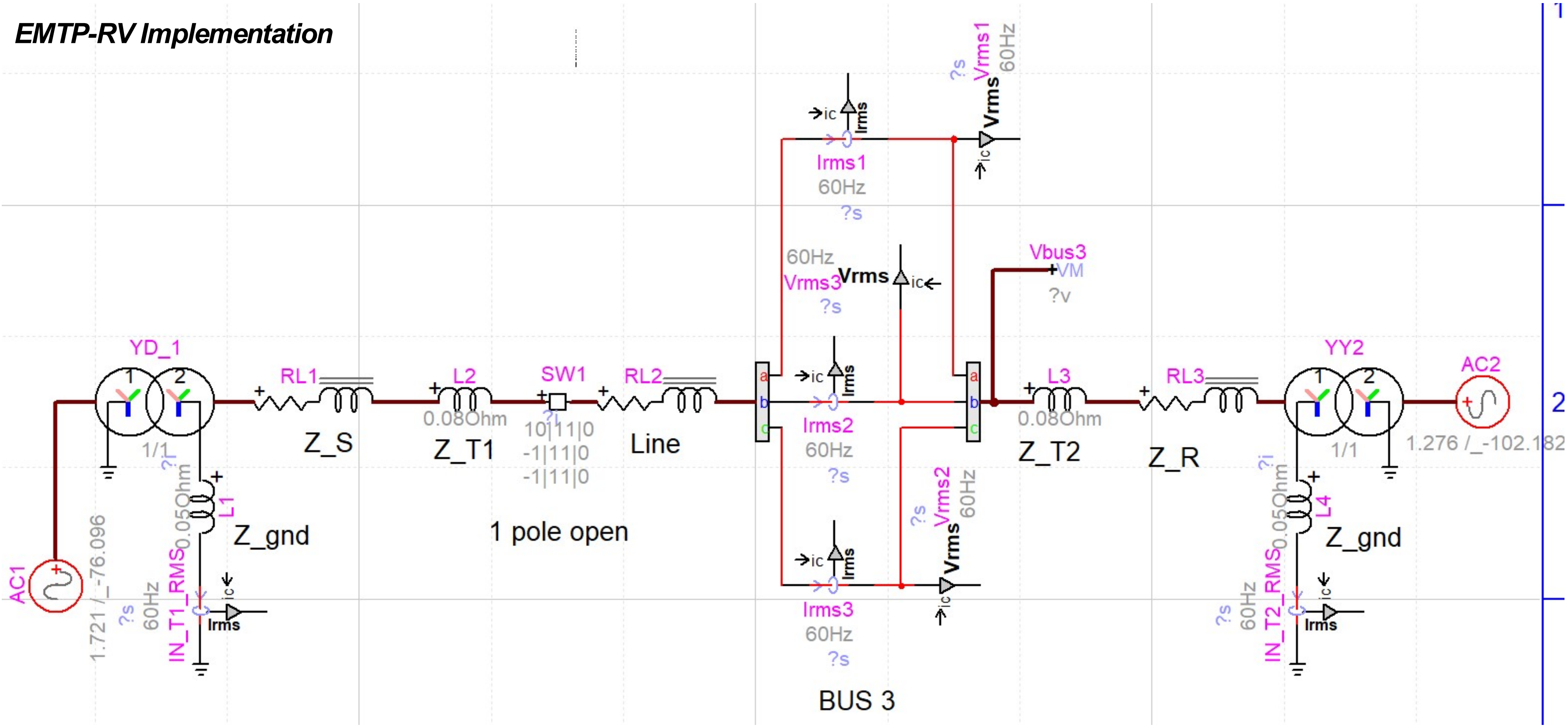




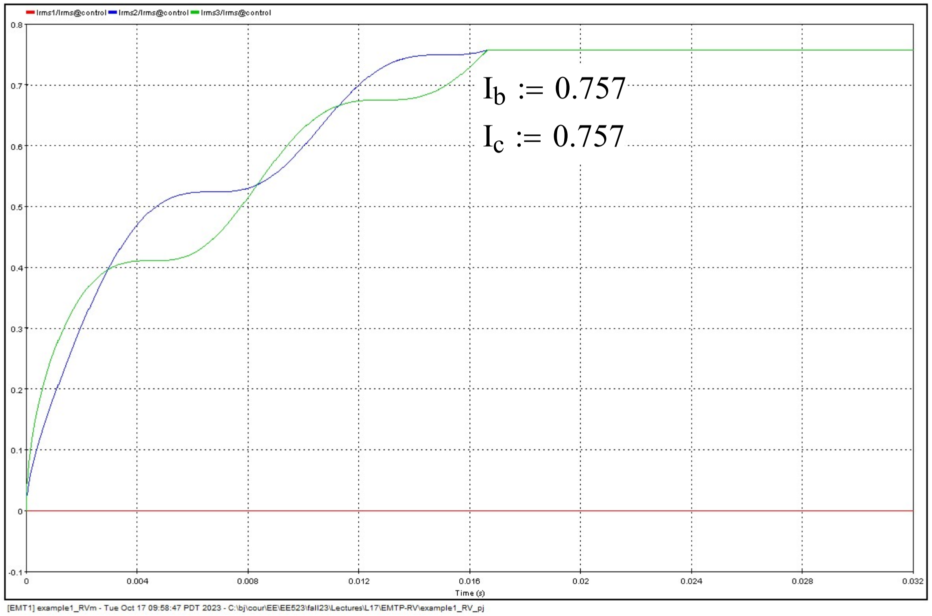

Main : RMS line currents
MagIA
MagIB
MagIC
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
(A)
sec
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14


Main : RMS Bus 3 Voltages
MagV3A
MagV3B
MagV3B
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
(A)
sec
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14

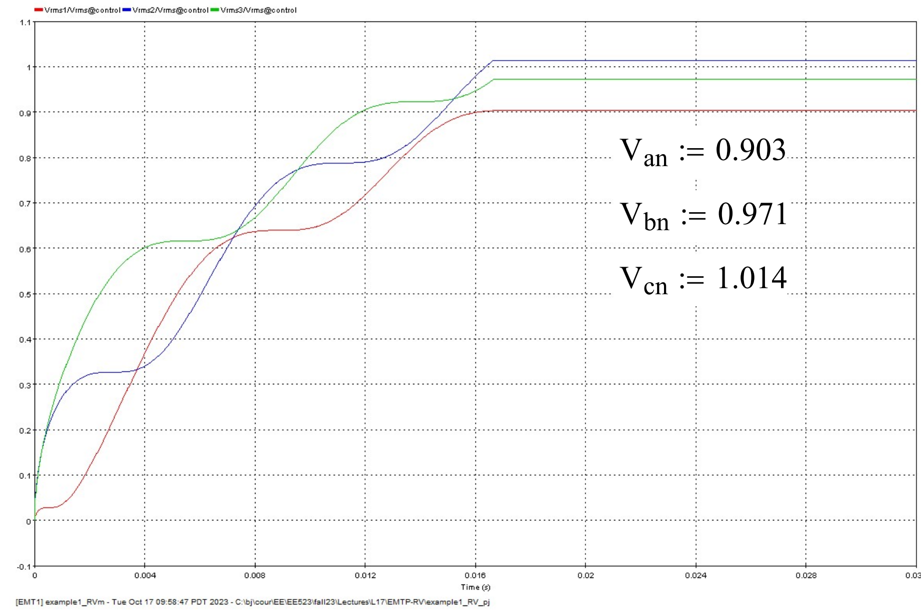
EMTP-RV Implementation



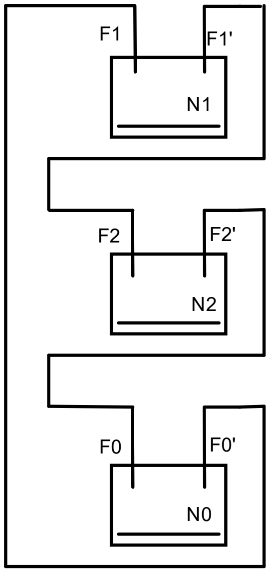
Currents



Voltages



Now solve the two phase open circuit below for the sequence currents:



$$I_1 := \frac{V_{equiv}}{Z_{1FF'} + Z_{2FF'} + Z_{0FF'}} \qquad I_1 = (0.2 - 0.12i)\cdot pu$$

$$|I_1| = 0.23\cdot pu \qquad \arg(I_1) = -31.79\cdot deg$$

$$I_2 := I_1 \qquad I_0 := I_1$$

$$I_{abc} := A_{012}\cdot\begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix} \qquad \overrightarrow{|I_{abc}|} = \begin{pmatrix} 0.69 \\ 0 \\ 0 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg(I_{abc})} = \begin{pmatrix} -31.79 \\ 81.87 \\ 81.87 \end{pmatrix}\cdot deg$$

$$V_{3new1} := E_2 + I_1\cdot j\cdot(X_{1Mach} + X_T) \qquad V_{3new1} = (0.92 - 0.14i)\cdot pu$$

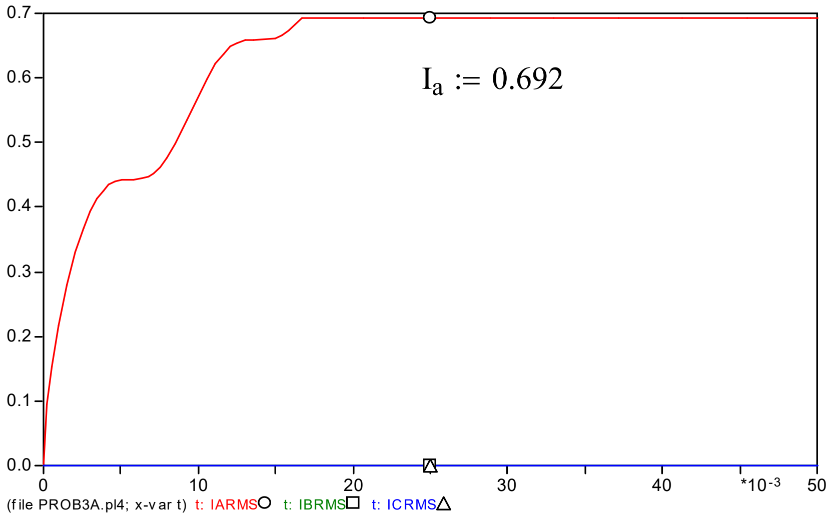
$$V_{3new2} := 0 + I_2\cdot j\cdot(X_{2Mach} + X_T) \qquad V_{3new2} = (0.03 + 0.05i)\cdot pu$$

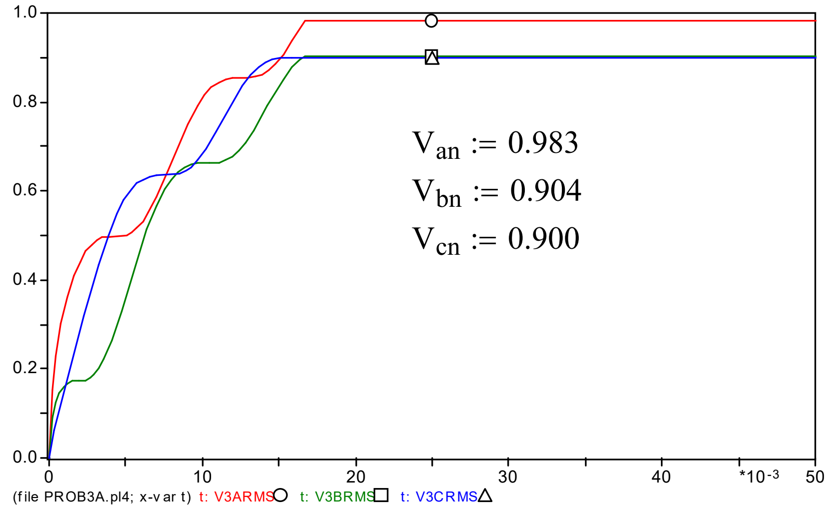
$$V_{3new0} := 0 + I_0\cdot j\cdot(X_{0Mach} + X_T + 3\cdot X_{nMach}) \qquad V_{3new0} = (0.03 + 0.05i)\cdot pu$$

$$V_{3newABC} := A_{012}\cdot\begin{pmatrix} V_{3new0} \\ V_{3new1} \\ V_{3new2} \end{pmatrix} \qquad \overrightarrow{|V_{3newABC}|} = \begin{pmatrix} 0.983 \\ 0.905 \\ 0.901 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg(V_{3newABC})} = \begin{pmatrix} -1.6 \\ -132.16 \\ 107.93 \end{pmatrix}\cdot deg$$

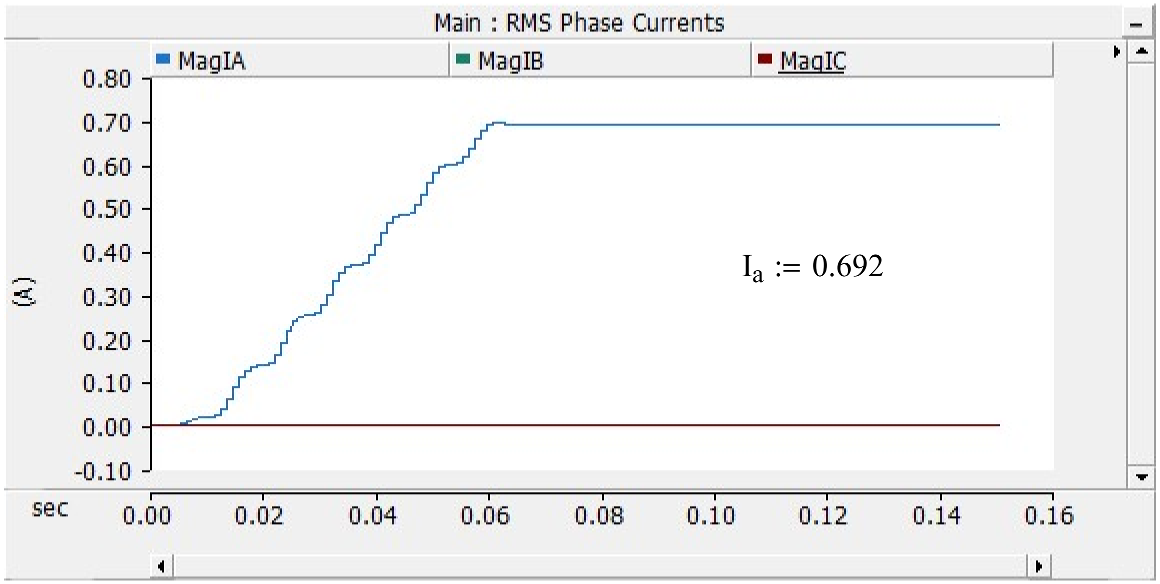
$$\Delta V_{ABC} := 1.0\cdot\begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} - V_{3newABC} \qquad \overrightarrow{|\Delta V_{ABC}|} = \begin{pmatrix} 0.03 \\ 0.22 \\ 0.22 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg(\Delta V_{ABC})} = \begin{pmatrix} 58.21 \\ -61.27 \\ 177.7 \end{pmatrix}\cdot deg$$

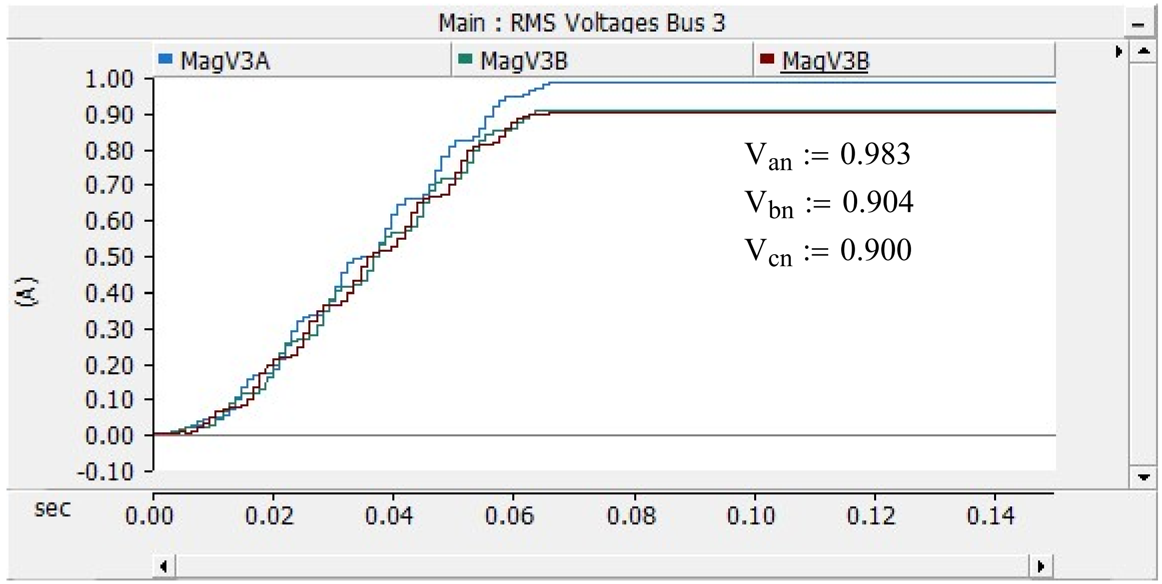
ATP Simulation Results:



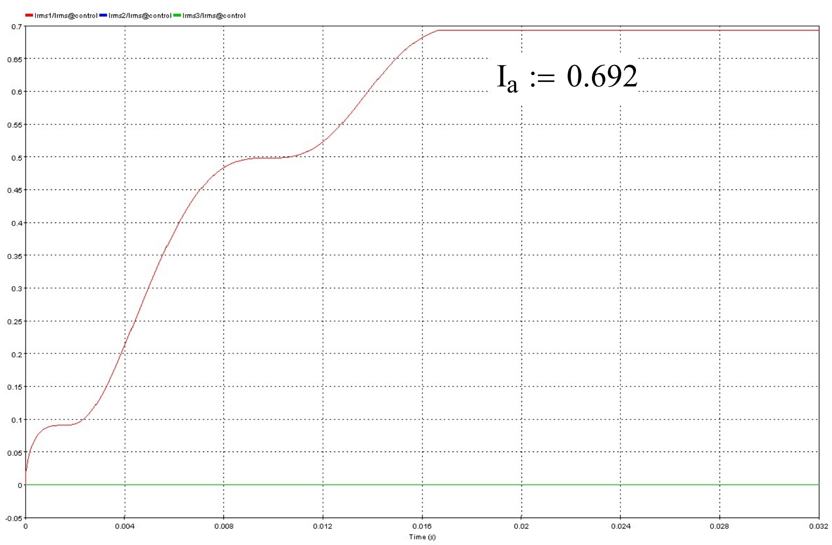


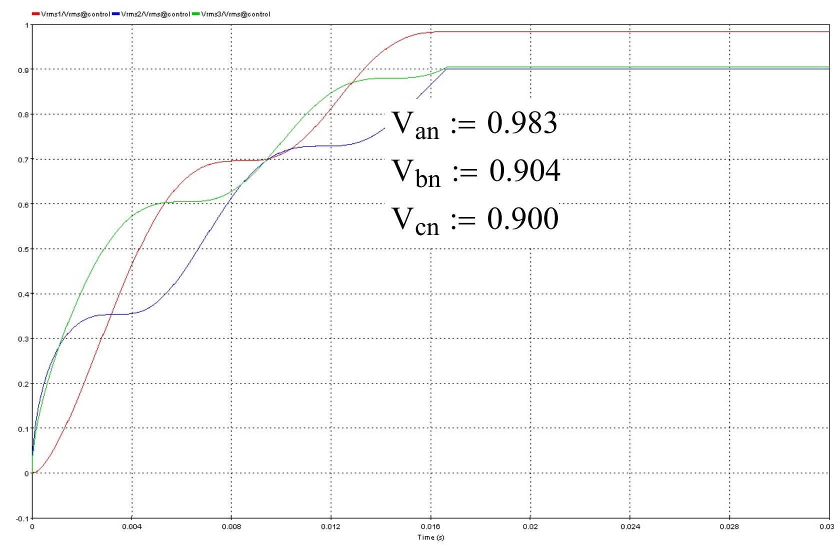
PSCAD/EMTDC Simulation Results:



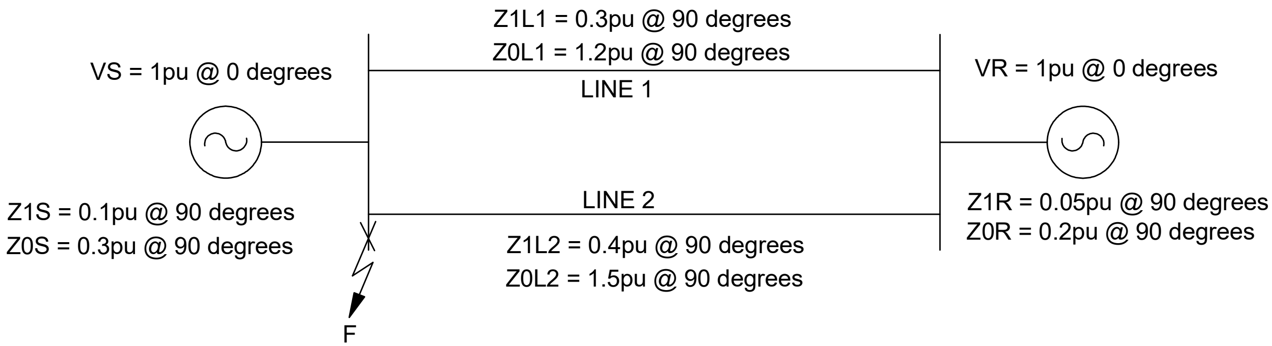


EMTP-RV Simulation Results:



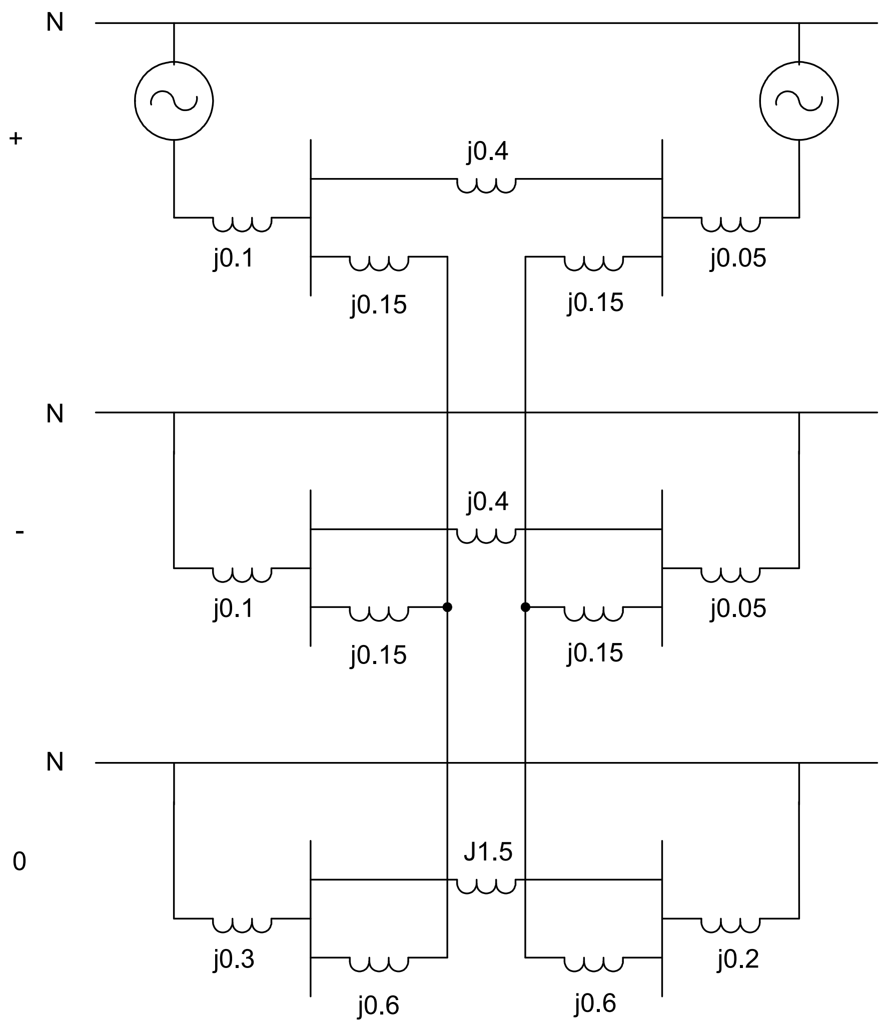


Example 2 For the system shown below, develop the sequence connection diagram for a single-phase open on Line 1.



$Z_{1S} := j\cdot 0.1pu$ $\quad Z_{1R} := j\cdot 0.05pu$ $\quad Z_{0S} := j\cdot 0.3pu$ $\quad Z_{0R} := j\cdot 0.2pu$

$Z_{1L1} := j\cdot 0.3$ $\quad Z_{1L2} := j\cdot 0.4$ $\quad Z_{0L1} := j\cdot 1.2$ $\quad Z_{0L2} := j\cdot 1.5$



$$Z_{1equiv} := \frac{Z_{1L1}}{2} + \left(\frac{1}{Z_{1S} + Z_{1R}} + \frac{1}{Z_{1L2}}\right)^{-1} + \frac{Z_{1L1}}{2}$$

$$Z_{1equiv} = 0.41i \cdot pu$$

$$Z_{2equiv} := Z_{1equiv}$$

$$Z_{0equiv} := Z_{0L1} + \left(\frac{1}{Z_{0S} + Z_{0R}} + \frac{1}{Z_{0L2}}\right)^{-1}$$

$$Z_{0equiv} = 1.58i \cdot pu$$

Using the sequence diagrams above calculate the positive-, negative-, and zero-sequence currents on Line 2 with VR = 1pu @ 20 degrees.

$V_S := 1pu \cdot e^{j \cdot 0deg}$ $V_R := 1pu \cdot e^{j \cdot 20deg}$

Total prefault current:

$$I_{sourceprefault} := \frac{V_S - V_R}{Z_{1S} + Z_{1R} + \left(\frac{1}{Z_{1L1}} + \frac{1}{Z_{1L2}}\right)^{-1}} \qquad \left|I_{sourceprefault}\right| = 1.08 \cdot pu \qquad \arg\left(I_{sourceprefault}\right) = -170 \cdot deg$$

Current dividers to find the current in lines 1 and 2:

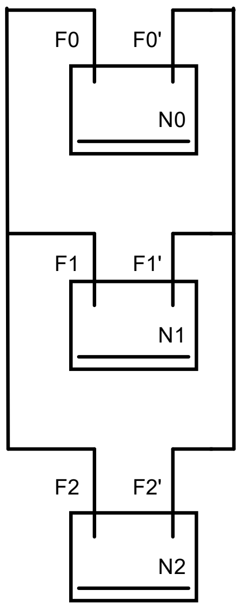
$$I_{L1\_prefault} := I_{sourceprefault} \cdot \left(\frac{Z_{1L2}}{Z_{1L1} + Z_{1L2}}\right) \qquad \left|I_{L1\_prefault}\right| = 0.62 \cdot pu \qquad \arg\left(I_{L1\_prefault}\right) = -170 \cdot deg$$

$$I_{L2\_prefault} := I_{sourceprefault} \cdot \left(\frac{Z_{1L1}}{Z_{1L1} + Z_{1L2}}\right) \qquad \left|I_{L2\_prefault}\right| = 0.46 \cdot pu \qquad \arg\left(I_{L2\_prefault}\right) = -170 \cdot deg$$

$$I_{ABCL1\_prefault} := I_{L1\_prefault} \cdot \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} \qquad \overrightarrow{\left|I_{ABCL1\_prefault}\right|} = \begin{pmatrix} 0.62 \\ 0.62 \\ 0.62 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABCL1\_prefault}\right)} = \begin{pmatrix} -170 \\ 70 \\ -50 \end{pmatrix} \cdot deg$$

$$I_{ABCL2\_prefault} := I_{L2\_prefault} \cdot \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} \qquad \overrightarrow{\left|I_{ABCL2\_prefault}\right|} = \begin{pmatrix} 0.46 \\ 0.46 \\ 0.46 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABCL2\_prefault}\right)} = \begin{pmatrix} -170 \\ 70 \\ -50 \end{pmatrix} \cdot deg$$

Phase A open analysis:



Equivalent voltage source for phase A open analysis:

$$V_{se} := V_S - V_R \qquad V_{se} = (0.06 - 0.34i)\cdot pu$$

Norton Equivalent Current: $I_{se} := \dfrac{V_{se}}{Z_{1R} + Z_{1S}}$ $\qquad I_{se} = (-2.28 - 0.4i)\cdot pu$

Equivalent Parallel Impedance: $Z_{eq} := \left(\dfrac{1}{Z_{1L2}} + \dfrac{1}{Z_{1S} + Z_{1R}}\right)^{-1}$ $\qquad Z_{eq} = 0.11i\cdot pu$

Convert back to Thevenin Equivalent Voltage

$$V_f := Z_{eq}\cdot I_{se} \qquad \left|V_f\right| = 0.25\cdot pu \qquad \arg\left(V_f\right) = -80\cdot deg$$

Positive sequence current in line 1:

$$I_{1L1\_open} := \frac{V_f}{Z_{1equiv} + \left(\dfrac{1}{Z_{2equiv}} + \dfrac{1}{Z_{0equiv}}\right)^{-1}} \qquad \left|I_{1L1\_open}\right| = 0.34\cdot pu \qquad \arg\left(I_{1L1\_open}\right) = -170\cdot deg$$

Negative sequence current in line 1 (current divider on the line 1 current)

$$I_{2L1\_open} := -I_{1L1\_open}\cdot\frac{Z_{0equiv}}{Z_{2equiv} + Z_{0equiv}} \qquad \left|I_{2L1\_open}\right| = 0.27\cdot pu \qquad \arg\left(I_{2L1\_open}\right) = 10\cdot deg$$

Zero sequence current in line 1 (current divider on the line 1 current)

$$I_{0L1\_open} := -I_{1L1\_open} \cdot \frac{Z_{2equiv}}{Z_{2equiv} + Z_{0equiv}}$$

$\left|I_{0L1\_open}\right| = 0.07 \cdot pu$ $\arg\left(I_{0L1\_open}\right) = 10 \cdot deg$

$$I_{ABC\_Line1} := A_{012} \cdot \begin{pmatrix} I_{0L1\_open} \\ I_{1L1\_open} \\ I_{2L1\_open} \end{pmatrix}$$

$\overrightarrow{\left|I_{ABC\_Line1}\right|} = \begin{pmatrix} 0 \\ 0.545 \\ 0.545 \end{pmatrix} \cdot pu$

$\arg\left(I_{ABC\_Line1_1}\right) = 88.74 \cdot deg$

$\arg\left(I_{ABC\_Line1_2}\right) = -68.74 \cdot deg$

Note that the magnitude on phase A is 0 and a little smaller on the unfaulted phases. There is also a phase shift compared to prefault

Now to fine the line 2 current, we need to do another current divider on each of the sequence currents from line 1, since the sequnce currents could either pass through the sources or line to to return to line 1.

Positive sequence load current in line two ignoring open line

$$I_{LineA2} := \frac{V_S - V_R}{Z_{1S} + Z_{1L2} + Z_{1R}}$$

$\left|I_{LineA2}\right| = 0.631$

$\arg\left(I_{LineA2}\right) = -170 \cdot deg$

$$I_{1L2} := -I_{1L1\_open} \cdot \left(\frac{Z_{1S} + Z_{1R}}{Z_{1S} + Z_{1R} + Z_{1L2}} \right) + I_{LineA2}$$

$$\left| I_{1L2} \right| = 0.54 \cdot pu \qquad \arg\left(I_{1L2}\right) = -170 \cdot deg$$

$$I_{2L2} := -I_{2L1\_open} \cdot \left(\frac{Z_{1S} + Z_{1R}}{Z_{1S} + Z_{1R} + Z_{1L2}} \right)$$

$$\left| I_{2L2} \right| = 0.07 \cdot pu \qquad \arg\left(I_{2L2}\right) = -170 \cdot deg$$

$$I_{0L2} := -I_{0L1\_open} \cdot \left(\frac{Z_{0S} + Z_{0R}}{Z_{0S} + Z_{0R} + Z_{0L2}} \right)$$

$$\left| I_{0L2} \right| = 0.02 \cdot pu \qquad \arg\left(I_{0L2}\right) = -170 \cdot deg$$

$$I_{ABC\_Line2} := A_{012} \cdot \begin{pmatrix} I_{0L2} \\ I_{1L2} \\ I_{2L2} \end{pmatrix}$$

$$\overrightarrow{\left| I_{ABC\_Line2} \right|} = \begin{pmatrix} 0.63 \\ 0.494 \\ 0.494 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_Line2}\right)} = \begin{pmatrix} -170 \\ 64.29 \\ -44.29 \end{pmatrix} \cdot deg$$

- See course web page for ATP, PSCAD/EMTDC, and EMTP-RV examples