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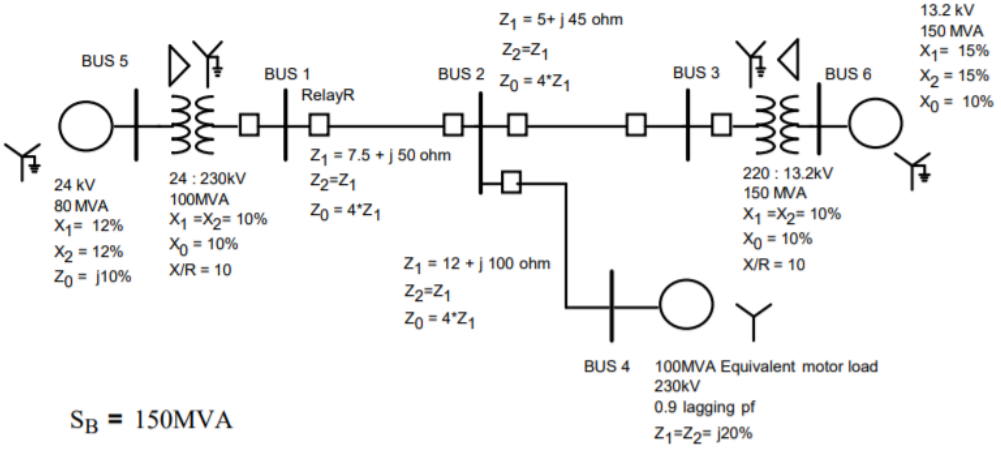
HWK3 - ECE523

In [1]:
```
# Import Modules
import numpy as np
import matplotlib.pyplot as plt
from tabulate import tabulate
import electricpy as ep
from electricpy import fault as flt
from electricpy.constants import *
```

Problem 1:

1. Create positive, negative and zero sequence Ybus and Zbus matrices for the system below to study faults on the line between BUS 1 and BUS 2. Use M=0.6



S_B = 150MVA

Start voltage bases using rated voltage for the generator at BUS 5

In [2]:

```
# Define Per-Unit Bases
Sbase = 150*M
Vbase5 = 24*k
Vbase1234 = 230*k
Vbase6 = Vbase1234 *13.2/220
Zbase1234 = ep.zpu(Sbase,Vbase1234)

# Evaluate Per-Unit Line Impedances
Z12_1 = (7.5 + 50j)/Zbase1234
Z12_0 = 4*Z12_1
Z23_1 = (5 + 45j)  /Zbase1234
Z23_0 = 4*Z23_1
Z24_1 = (12 + 100j)/Zbase1234
Z24_0 = 4*Z24_1
print("Z12:",np.around(Z12_1,3),
      "\nZ23:",np.round(Z23_1,3),
      "\nZ24:",np.round(Z24_1,3))

# Define System Terms
percent = 1/100
g5_x1 = 12j*percent
g5_x2 = g5_x1
g5_x0 = 10j*percent
t15_1 = ep.puchgbase(ep.rxrecompose(10*percent,10),ep.zpu(100*M,230*k),Zbase1234)
t15_2 = t15_1
t15_0 = t15_1
g6_x1 = 15j*percent
g6_x2 = g6_x1
g6_x0 = 10j*percent
t36_1 = ep.puchgbase(ep.rxrecompose(10*percent,10),ep.zpu(150*M,220*k),Zbase1234)
t36_2 = t36_1
t36_0 = t36_1
m4_x1 = 20j*percent
m4_x2 = m4_x1

# Since we're considering a fault at location M, we must create a
# ficticious bus for the location M. Let's Define two "new lines"
Mdist = 0.6
Z1M_1 = Z12_1 * Mdist
Z1M_0 = Z12_0 * Mdist
ZM2_1 = Z12_1 * (1-Mdist)
ZM2_0 = Z12_0 * (1-Mdist)

# Define the Positive-Sequence Y-Bus Matrix, Will be 7x7 (include M bus)
ybus1 = np.array([
    [1/(t15_1)+1/(Z1M_1),  0,  0,  0,  -en30/(t15_1),  0,  -1/(Z1M_1)],
    [0,  1/(ZM2_1)+1/(Z23_1)+1/(Z24_1),  -1/(Z23_1), -1/(Z24_1),  0,  0,  -1/(ZM2_1)],
    [0,  -1/(Z23_1),  1/(Z23_1)+1/(t36_1),  0,  0,  -en30/(t36_1),  0],
    [0,  -1/(Z24_1),  0,  1/(Z24_1)+1/(m4_x1),  0,  0,  0],
    [-e30/(t15_1),  0,  0,  0,  1/(t15_1)+1/(g5_x1),  0,  0],
    [0,  0,  -e30/(t36_1),  0,  0,  1/(t36_1)+1/(g6_x1),  0],
    [-1/(Z1M_1),  -1/(ZM2_1),  0,  0,  0,  0,  1/(Z1M_1)+1/(ZM2_1)]
])
zbus1 = np.linalg.inv(ybus1)
LATEXybus1 = ep.clatex(ybus1,round=1,polar=False,double=True)
LATEXzbus1 = ep.clatex(zbus1,polar=False,double=True)

# Define the Negative-Sequence Y-Bus Matrix
ybus2 = np.array([
    [1/(t15_2)+1/(Z1M_1),  0,  0,  0,  -e30/(t15_2),  0,  -1/(Z1M_1)],
    [0,  1/(ZM2_1)+1/(Z23_1)+1/(Z24_1),  -1/(Z23_1), -1/(Z24_1),  0,  0,  -1/(ZM2_1)],
    [0,  -1/(Z23_1),  1/(Z23_1)+1/(t36_2),  0,  0,  -e30/(t36_2),  0],
    [0,  -1/(Z24_1),  0,  1/(Z24_1)+1/(m4_x2),  0,  0,  0],
    [-en30/(t15_2),  0,  0,  0,  1/(t15_2)+1/(g5_x2),  0,  0],
    [0,  0,  -en30/(t36_2),  0,  0,  1/(t36_2)+1/(g6_x2),  0],
    [-1/(Z1M_1),  -1/(ZM2_1),  0,  0,  0,  0,  1/(Z1M_1)+1/(ZM2_1)]
])
zbus2 = np.linalg.inv(ybus2)
LATEXybus2 = ep.clatex(ybus2,round=1,polar=False,double=True)
LATEXzbus2 = ep.clatex(zbus2,polar=False,double=True)

# Define the Zero-Sequence Y-Bus Matrix
ybus0 = np.array([
    [1/(t15_0)+1/(Z1M_0),  0,  0,  0,  0,  0,  -1/(Z1M_0)],
    [0,  1/(ZM2_0)+1/(Z23_0)+1/(Z24_0),  -1/(Z23_0), -1/(Z24_0),  0,  0,  -1/(ZM2_0)],
    [0,  -1/(Z23_0),  1/(Z23_0)+1/(t36_0),  0,  0,  0,  0],
    [0,  -1/(Z24_0),  0,  1/(Z24_0),  0,  0,  0],
    [0,  0,  0,  0,  1/(t15_0)+1/(g5_x0),  0,  0],
    [0,  0,  0,  0,  0,  1/(t36_0)+1/(g6_x0),  0],
    [-1/(Z1M_0),  -1/(ZM2_0),  0,  0,  0,  0,  1/(Z1M_0)+1/(ZM2_0)]
])
zbus0 = np.linalg.inv(ybus0)
LATEXybus0 = ep.clatex(ybus0,round=1,polar=False,double=True)
LATEXzbus0 = ep.clatex(zbus0,polar=False,double=True)
```

```
Z12: (0.021+0.142j)
Z23: (0.014+0.128j)
```

```
Z24: (0.034+0.284j)
```

Positive Sequence:

Y-Bus Matrix:

$$\begin{bmatrix} 2.4 - j18.1 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 2.7 + j6.0 & 0.0 - j0.0 & -1.7 + j11.5 \\ 0.0 - j0.0 & 3.9 - j28.5 & -0.9 + j7.7 & -0.4 + j3.5 & 0.0 - j0.0 & 0.0 - j0.0 & -2.6 + j17.2 \\ 0.0 - j0.0 & -0.9 + j7.7 & 1.9 - j18.6 & 0.0 - j0.0 & 0.0 - j0.0 & 4.5 + j9.9 & 0.0 - j0.0 \\ 0.0 - j0.0 & -0.4 + j3.5 & 0.0 - j0.0 & 0.4 - j8.5 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 \\ -3.9 + j5.4 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.7 - j14.9 & 0.0 - j0.0 & 0.0 - j0.0 \\ 0.0 - j0.0 & 0.0 - j0.0 & -6.3 + j8.8 & 0.0 - j0.0 & 0.0 - j0.0 & 1.1 - j17.5 & 0.0 - j0.0 \\ -1.7 + j11.5 & -2.6 + j17.2 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 4.3 - j28.7 \end{bmatrix}$$

Z-Bus Matrix:

$$\begin{bmatrix} 0.011 + j0.153 & 0.004 + j0.091 & 0.001 + j0.059 & -0.001 + j0.038 & 0.035 + j0.058 & 0.018 + j0.032 & 0.007 + j0.116 \\ 0.004 + j0.091 & 0.01 + j0.139 & 0.004 + j0.091 & 0.0 + j0.057 & 0.02 + j0.035 & 0.029 + j0.049 & 0.008 + j0.12 \\ 0.001 + j0.059 & 0.004 + j0.091 & 0.009 + j0.143 & -0.001 + j0.038 & 0.012 + j0.023 & 0.046 + j0.076 & 0.003 + j0.078 \\ -0.001 + j0.038 & 0.0 + j0.057 & -0.001 + j0.038 & 0.004 + j0.141 & 0.007 + j0.015 & 0.01 + j0.021 & -0.0 + j0.049 \\ -0.033 + j0.059 & -0.021 + j0.035 & -0.014 + j0.022 & -0.01 + j0.014 & 0.002 + j0.097 & -0.001 + j0.016 & -0.026 + j0.045 \\ -0.019 + j0.032 & -0.028 + j0.049 & -0.043 + j0.078 & -0.013 + j0.019 & -0.001 + j0.016 & 0.003 + j0.112 & -0.024 + j0.042 \\ 0.007 + j0.116 & 0.008 + j0.12 & 0.003 + j0.078 & -0.0 + j0.049 & 0.026 + j0.044 & 0.024 + j0.042 & 0.012 + j0.152 \end{bmatrix}$$

Negative Sequence:

Y-Bus Matrix:

$$\begin{bmatrix} 2.4 - j18.1 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & -3.9 + j5.4 & 0.0 - j0.0 & -1.7 + j11.5 \\ 0.0 - j0.0 & 3.9 - j28.5 & -0.9 + j7.7 & -0.4 + j3.5 & 0.0 - j0.0 & 0.0 - j0.0 & -2.6 + j17.2 \\ 0.0 - j0.0 & -0.9 + j7.7 & 1.9 - j18.6 & 0.0 - j0.0 & 0.0 - j0.0 & -6.3 + j8.8 & 0.0 - j0.0 \\ 0.0 - j0.0 & -0.4 + j3.5 & 0.0 - j0.0 & 0.4 - j8.5 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 \\ 2.7 + j6.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.7 - j14.9 & 0.0 - j0.0 & 0.0 - j0.0 \\ 0.0 - j0.0 & 0.0 - j0.0 & 4.5 + j9.9 & 0.0 - j0.0 & 0.0 - j0.0 & 1.1 - j17.5 & 0.0 - j0.0 \\ -1.7 + j11.5 & -2.6 + j17.2 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 4.3 - j28.7 \end{bmatrix}$$

Z-Bus Matrix:

$$\begin{bmatrix} 0.011 + j0.153 & 0.004 + j0.091 & 0.001 + j0.059 & -0.001 + j0.038 & -0.033 + j0.059 & -0.019 + j0.032 & 0.007 + j0.116 \\ 0.004 + j0.091 & 0.01 + j0.139 & 0.004 + j0.091 & 0.0 + j0.057 & -0.021 + j0.035 & -0.028 + j0.049 & 0.008 + j0.12 \\ 0.001 + j0.059 & 0.004 + j0.091 & 0.009 + j0.143 & -0.001 + j0.038 & -0.014 + j0.022 & -0.043 + j0.078 & 0.003 + j0.078 \\ -0.001 + j0.038 & 0.0 + j0.057 & -0.001 + j0.038 & 0.004 + j0.141 & -0.01 + j0.014 & -0.013 + j0.019 & -0.0 + j0.049 \\ 0.035 + j0.058 & 0.02 + j0.035 & 0.012 + j0.023 & 0.007 + j0.015 & 0.002 + j0.097 & -0.001 + j0.016 & 0.026 + j0.044 \\ 0.018 + j0.032 & 0.029 + j0.049 & 0.046 + j0.076 & 0.01 + j0.021 & -0.001 + j0.016 & 0.003 + j0.112 & 0.024 + j0.042 \\ 0.007 + j0.116 & 0.008 + j0.12 & 0.003 + j0.078 & -0.0 + j0.049 & -0.026 + j0.045 & -0.024 + j0.042 & 0.012 + j0.152 \end{bmatrix}$$

Zero Sequence:

Y-Bus Matrix:

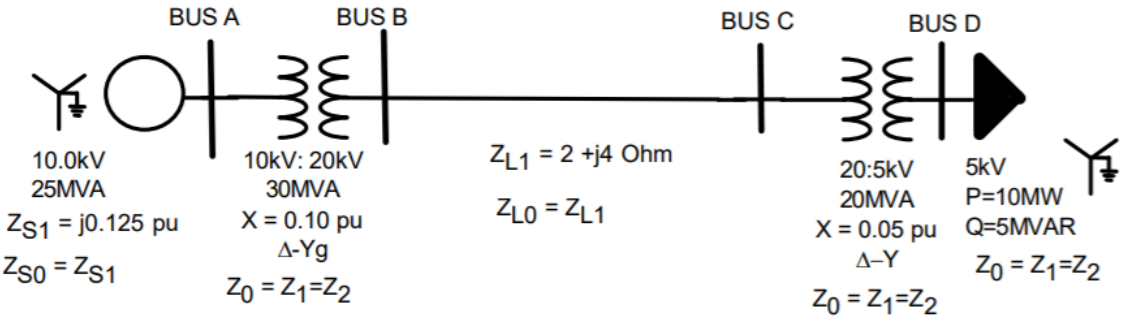
$$\begin{bmatrix} 1.1 - j9.5 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & -0.4 + j2.9 \\ 0.0 - j0.0 & 1.0 - j7.1 & -0.2 + j1.9 & -0.1 + j0.9 & 0.0 - j0.0 & 0.0 - j0.0 & -0.6 + j4.3 \\ 0.0 - j0.0 & -0.2 + j1.9 & 1.3 - j12.8 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 \\ 0.0 - j0.0 & -0.1 + j0.9 & 0.0 - j0.0 & 0.1 - j0.9 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 \\ 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.7 - j16.6 & 0.0 - j0.0 & 0.0 - j0.0 \\ 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 1.1 - j20.8 & 0.0 - j0.0 \\ -0.4 + j2.9 & -0.6 + j4.3 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 1.1 - j7.2 \end{bmatrix}$$

Z-Bus Matrix:

$$\begin{bmatrix} 0.014 + j0.133 & 0.006 + j0.068 & 0.001 + j0.01 & 0.006 + j0.068 & 0.0 - j0.0 & 0.0 - j0.0 & 0.009 + j0.094 \\ 0.006 + j0.068 & 0.04 + j0.327 & 0.006 + j0.05 & 0.04 + j0.327 & 0.0 - j0.0 & 0.0 - j0.0 & 0.026 + j0.224 \\ 0.001 + j0.01 & 0.006 + j0.05 & 0.009 + j0.085 & 0.006 + j0.05 & 0.0 - j0.0 & 0.0 - j0.0 & 0.004 + j0.034 \\ 0.006 + j0.068 & 0.04 + j0.327 & 0.006 + j0.05 & 0.176 + j1.462 & 0.0 - j0.0 & 0.0 - j0.0 & 0.026 + j0.224 \\ 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.002 + j0.06 & 0.0 - j0.0 & 0.0 - j0.0 \\ 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.0 - j0.0 & 0.002 + j0.048 & 0.0 - j0.0 \\ 0.009 + j0.094 & 0.026 + j0.224 & 0.004 + j0.034 & 0.026 + j0.224 & 0.0 - j0.0 & 0.0 - j0.0 & 0.04 + j0.308 \end{bmatrix}$$

Problem 2:

2. Analyze the following faults. Use Sbase=25 MVA and a voltage base of 5kV at BUS D. You can neglect load current in your fault current calculations. Treat all buses as being at 1.0pu magnitude prior to the fault.
   a. Three phase fault at Bus C. Find V and I at the fault location and at BUS A
   b. SLG fault with Rf=0 at Bus C. Find V and I at the fault location and at BUS A
   c. LL fault with Rf=0 at Bus C. Find V and I at the fault location and at BUS A
   d. DLG fault with Rf=Rg=0 at Bus C, Find V and I at the fault location and at BUS A
   e. Compare the fault current magnitudes and voltages between the different fault types, plus for faults at fault location at BUS B



In [3]:

```
# Define Per-Unit Bases
Sbase = 25*M
VbaseD = 5*k
VbaseBC = 20*k
VbaseA = 10*k
ZbaseBC = ep.zpu(Sbase,VbaseBC)

# Evaluate Load Impedance
Sload = 10*M + 5j*M
Zload = ep.powerimpedance(Sload,VbaseD)
print("Load Impedance:",np.around(Zload,3))

# Set Impedances in Appropriate Base
Zsrc = 0.125j
tab_1 = ep.puchgbase(0.10j,ep.zpu(30*M,20*k),ZbaseBC)
tcd_1 = ep.puchgbase(0.05j,ep.zpu(20*M,20*k),ZbaseBC)
Zline = (2+4j) / ZbaseBC
print("Transformer 1:",tab_1,
      "\nTransformer 2:",tcd_1,
      "\nZline:",Zline)

# Evaluate the Z-Bus Matricies
zbus1 = np.linalg.inv(np.array([
    [1/Zsrc+1/tab_1,  -e30/tab_1,  0,  0],
    [-en30/tab_1,  1/tab_1+1/Zline,  -1/Zline,  0],
    [0,  -1/Zline,  1/Zline+1/tcd_1,  -e30/tcd_1],
    [0,  0, -en30/tcd_1,  1/tcd_1+1/Zload]
]))
zbus2 = np.linalg.inv(np.array([
    [1/Zsrc+1/tab_1,  -en30/tab_1,  0,  0],
    [-e30/tab_1,  1/tab_1+1/Zline,  -1/Zline,  0],
    [0,  -1/Zline,  1/Zline+1/tcd_1,  -en30/tcd_1],
    [0,  0, -e30/tcd_1,  1/tcd_1+1/Zload]
]))
zbus0 = np.linalg.inv(np.array([
    [1/Zsrc,  0,  0,  0],
    [0,  1/tab_1+1/Zline,  -1/Zline,  0],
    [0,  -1/Zline,  1/Zline+1/tcd_1,  0],
    [0,  0, 0,  1/Zload]
]))
print("\nPositive Sequence Z-Bus:")
print(tabulate(np.asarray(np.around(zbus1,3),dtype=str),tablefmt="fancy_grid"))
print("\nNegative Sequence Z-Bus:")
print(tabulate(np.asarray(np.around(zbus2,3),dtype=str),tablefmt="fancy_grid"))
print("\nZero Sequence Z-Bus:")
print(tabulate(np.asarray(np.around(zbus0,3),dtype=str),tablefmt="fancy_grid"))
```

```
Load Impedance: (2.5+5j)
Transformer 1: 0.08333333333333334j
Transformer 2: 0.0625j
Zline: (0.125+0.25j)
```

Positive Sequence Z-Bus:

(0.001+0.123j)	(-0.059+0.106j)	(-0.056+0.101j)	(-0.098+0.059j)
(0.062+0.104j)	(0.003+0.202j)	(0.003+0.192j)	(-0.092+0.167j)
(0.059+0.099j)	(0.003+0.192j)	(0.122+0.422j)	(-0.102+0.422j)
(0.1+0.055j)	(0.099+0.163j)	(0.315+0.3j)	(0.124+0.474j)

Negative Sequence Z-Bus:

(0.001+0.123j)	(0.062+0.104j)	(0.059+0.099j)	(0.1+0.055j)
(-0.059+0.106j)	(0.003+0.202j)	(0.003+0.192j)	(0.099+0.163j)
(-0.056+0.101j)	(0.003+0.192j)	(0.122+0.422j)	(0.315+0.3j)
(-0.098+0.059j)	(-0.092+0.167j)	(-0.102+0.422j)	(0.124+0.474j)

Zero Sequence Z-Bus:

0.125j	0j	0j	0j
0j	(0.005+0.067j)	(-0.004+0.012j)	0j
0j	(-0.004+0.012j)	(0.003+0.054j)	0j
0j	0j	0j	(2.5+5j)

In [4]:

```
# Evaluate The Thevenin Set For Fault Calculations
Zth = [zbus0[3,3],zbus1[3,3],zbus2[3,3]]
print("Sequence Impedances at Bus C:",np.around(Zth,3))

# A) Three-Phase
I012 = flt.phs3(1,Zth)
VA = flt.busvolt(1,3,1,zbus0,zbus1,zbus2,I012,sequence=False)
VC = flt.busvolt(3,3,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nThree-Phase Fault")
ep.cprint(ep.seq_to_phs(I012),"A",label=["IA","IB","IC"])
ep.cprint(VA,"V",["A-VA","A-VB","A-VC"])
ep.cprint(VC,"V",["C-VA","C-VB","C-VC"])

# B) SLG Fault:
I012 = flt.phs1g(1,Zth)
VA = flt.busvolt(1,3,1,zbus0,zbus1,zbus2,I012,sequence=False)
VC = flt.busvolt(3,3,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nSingle-Line-to-Ground Fault")
ep.cprint(ep.seq_to_phs(I012),"A",label=["IA","IB","IC"])
ep.cprint(VA,"V",["A-VA","A-VB","A-VC"])
ep.cprint(VC,"V",["C-VA","C-VB","C-VC"])

# C) LL Fault:
I012 = flt.phs2(1,Zth)
VA = flt.busvolt(1,3,1,zbus0,zbus1,zbus2,I012,sequence=False)
VC = flt.busvolt(3,3,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nLine-to-Line Fault")
ep.cprint(ep.seq_to_phs(I012),"A",label=["IA","IB","IC"])
ep.cprint(VA,"V",["A-VA","A-VB","A-VC"])
ep.cprint(VC,"V",["C-VA","C-VB","C-VC"])

# D) DLG Fault:
I012 = flt.phs2g(1,Zth)
VA = flt.busvolt(1,3,1,zbus0,zbus1,zbus2,I012,sequence=False)
VC = flt.busvolt(3,3,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nDouble-Line-to-Ground Fault")
ep.cprint(ep.seq_to_phs(I012),"A",label=["IA","IB","IC"])
ep.cprint(VA,"V",["A-VA","A-VB","A-VC"])
ep.cprint(VC,"V",["C-VA","C-VB","C-VC"])
```

```
Sequence Impedances at Bus C: [ 2.500+5.j     0.124+0.474j  0.124+0.474j]

Three-Phase Fault
[['IA 2.042 ∠ -75.369° A']
 ['IB 2.042 ∠ 164.631° A']
 ['IC 2.042 ∠ 44.631° A']]
[['A-VA 0.846 ∠ -11.119° V']
 ['A-VB 0.846 ∠ -131.119° V']
 ['A-VC 0.846 ∠ 108.881° V']]
[['C-VA 0.107 ∠ 12.454° V']
 ['C-VB 0.107 ∠ -107.546° V']
 ['C-VC 0.107 ∠ 132.454° V']]

Single-Line-to-Ground Fault
[['IA 0.458 ∠ -65.207° A']
 ['IB 0.0 ∠ 45.0° A']
 ['IC 0.0 ∠ 56.31° A']]
[['A-VA 0.972 ∠ -0.73° V']
 ['A-VB 1.0 ∠ -120.0° V']
 ['A-VC 0.997 ∠ 118.256° V']]
[['C-VA 0.86 ∠ -1.549° V']
 ['C-VB 0.966 ∠ -117.198° V']
 ['C-VC 0.978 ∠ 116.819° V']]

Line-to-Line Fault
[['IA 0.0 ∠ 0.0° A']
 ['IB 1.768 ∠ -165.369° A']
 ['IC 1.768 ∠ 14.631° A']]
[['A-VA 1.034 ∠ -6.353° V']
 ['A-VB 0.846 ∠ -131.119° V']
 ['A-VC 0.887 ∠ 122.126° V']]
[['C-VA 1.0 ∠ -0.0° V']
 ['C-VB 0.488 ∠ -169.327° V']
 ['C-VC 0.528 ∠ 170.13° V']]

Double-Line-to-Ground Fault
[['IA 0.0 ∠ -67.38° A']
 ['IB 1.798 ∠ -169.39° A']
 ['IC 1.747 ∠ 18.77° A']]
[['A-VA 1.027 ∠ -6.603° V']
 ['A-VB 0.846 ∠ -131.119° V']
 ['A-VC 0.886 ∠ 121.576° V']]
[['C-VA 0.967 ∠ -0.279° V']
 ['C-VB 0.465 ∠ -169.419° V']
 ['C-VC 0.506 ∠ 169.125° V']]
```

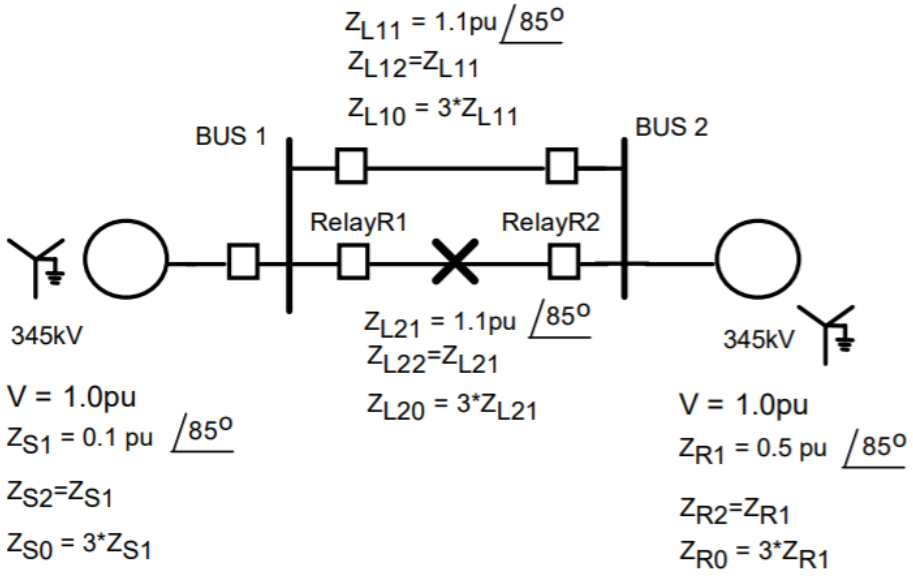
In [5]:

```
# Evaluate The Thevenin Set For Fault Calculations
Zth = [zbus0[2,2],zbus1[2,2],zbus2[2,2]]
print("Sequence Impedances at Bus B:",np.around(Zth,3))

# A) Three-Phase
I012 = flt.phs3(1,Zth)
VA = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
VC = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nThree-Phase Fault")
ep.cprint(ep.seq_to_phs(I012),"A",label=["IA","IB","IC"])
ep.cprint(VA,"V",["A-VA","A-VB","A-VC"])
ep.cprint(VC,"V",["C-VA","C-VB","C-VC"])

# B) SLG Fault:
I012 = flt.phs1g(1,Zth)
VA = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
VC = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nSingle-Line-to-Ground Fault")
ep.cprint(ep.seq_to_phs(I012),"A",label=["IA","IB","IC"])
ep.cprint(VA,"V",["A-VA","A-VB","A-VC"])
ep.cprint(VC,"V",["C-VA","C-VB","C-VC"])

# C) LL Fault:
I012 = flt.phs2(1,Zth)
VA = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
VC = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nLine-to-Line Fault")
ep.cprint(ep.seq_to_phs(I012),"A",label=["IA","IB","IC"])
ep.cprint(VA,"V",["A-VA","A-VB","A-VC"])
ep.cprint(VC,"V",["C-VA","C-VB","C-VC"])

# D) DLG Fault:
I012 = flt.phs2g(1,Zth)
VA = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
VC = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nDouble-Line-to-Ground Fault")
ep.cprint(ep.seq_to_phs(I012),"A",label=["IA","IB","IC"])
ep.cprint(VA,"V",["A-VA","A-VB","A-VC"])
ep.cprint(VC,"V",["C-VA","C-VB","C-VC"])
```

```
Sequence Impedances at Bus B: [ 0.003+0.054j  0.122+0.422j  0.122+0.422j]

Three-Phase Fault
[['IA 2.279 ∠ -73.893° A']
 ['IB 2.279 ∠ 166.107° A']
 ['IC 2.279 ∠ 46.107° A']]
[['A-VA 0.829 ∠ -13.68° V']
 ['A-VB 0.829 ∠ -133.68° V']
 ['A-VC 0.829 ∠ 106.32° V']]
[['C-VA 0.569 ∠ -12.278° V']
 ['C-VB 0.569 ∠ -132.278° V']
 ['C-VC 0.569 ∠ 107.722° V']]

Single-Line-to-Ground Fault
[['IA 3.226 ∠ -74.641° A']
 ['IB 0.0 ∠ 33.69° A']
 ['IC 0.0 ∠ 36.87° A']]
[['A-VA 0.784 ∠ -4.134° V']
 ['A-VB 1.0 ∠ -120.0° V']
 ['A-VC 0.965 ∠ 106.968° V']]
[['C-VA 0.523 ∠ -13.573° V']
 ['C-VB 0.901 ∠ -113.619° V']
 ['C-VC 0.976 ∠ 111.718° V']]

Line-to-Line Fault
[['IA 0.0 ∠ 0.0° A']
 ['IB 1.974 ∠ -163.893° A']
 ['IC 1.974 ∠ 16.107° A']]
[['A-VA 1.045 ∠ -7.325° V']
 ['A-VB 0.829 ∠ -133.68° V']
 ['A-VC 0.867 ∠ 122.324° V']]
[['C-VA 1.0 ∠ -0.0° V']
 ['C-VB 0.773 ∠ -141.477° V']
 ['C-VC 0.623 ∠ 129.381° V']]

Double-Line-to-Ground Fault
[['IA 0.0 ∠ 75.964° A']
 ['IB 3.32 ∠ 139.989° A']
 ['IC 3.463 ∠ 68.842° A']]
[['A-VA 0.866 ∠ -11.698° V']
 ['A-VB 0.829 ∠ -133.68° V']
 ['A-VC 0.823 ∠ 109.561° V']]
[['C-VA 0.763 ∠ -4.627° V']
 ['C-VB 0.517 ∠ -125.583° V']
 ['C-VC 0.55 ∠ 99.569° V']]
```

Problem 3:

3. Do the following for the circuit below. **Also check your results with a commercial fault program and show comparison in tables.**
   a. Calculate and sketch the positive, negative and zero sequence equivalent circuits based on a fault 40% of the way down line 2 (the lower of the two lines).
   b. Calculate the voltages and currents at RelayR1 and RelayR2, for SLG, LL, and DLG faults with Rf = 0. I recommend using Zbus matrix methods.
   c. Repeat the part (b) for a SLG fault, LL, and DLG with Rf = 0.75 pu. For the DLG put the fault resistance in the neutral to ground path.



In [16]:

```
# Define Impedances
zs1 = ep.phasor(0.1,85)
zl1 = ep.phasor(1.1,85)
zl13 = ep.phasor(1.1,85)*0.4
zl32 = ep.phasor(1.1,85)*0.6
zr1 = ep.phasor(0.5,85)
Rf = 0.75

# Generate Sequence Impedance Busses
zbus1 = np.linalg.inv(np.array([
    [1/zs1+1/zl1+1/zl13,  -1/zl1,  -1/zl13],
    [-1/zl1,  1/zl1+1/zl32+1/zr1,  -1/zl32],
    [-1/zl13,  -1/zl32,  1/zl13+1/zl32]
]))
zbus2 = zbus1
zbus0 = np.linalg.inv(np.array([
    [1/(zs1*3)+1/(zl1*3)+1/(zl13*3),  -1/(zl1*3),  -1/(zl13*3)],
    [-1/(zl1*3),  1/(zl1*3)+1/(zl32*3)+1/(zr1*3),  -1/(zl32*3)],
    [-1/(zl13*3),  -1/(zl32*3),  1/(zl13*3)+1/(zl32*3)]
]))
print("\nPositive Sequence Z-Bus:")
print(tabulate(np.asarray(np.around(zbus1,3),dtype=str),tablefmt="fancy_grid"))
print("\nNegative Sequence Z-Bus:")
print(tabulate(np.asarray(np.around(zbus2,3),dtype=str),tablefmt="fancy_grid"))
print("\nZero Sequence Z-Bus:")
print(tabulate(np.asarray(np.around(zbus0,3),dtype=str),tablefmt="fancy_grid"))
```

Positive Sequence Z-Bus:

(0.008+0.091j)	(0.004+0.043j)	(0.006+0.072j)
(0.004+0.043j)	(0.025+0.282j)	(0.012+0.139j)
(0.006+0.072j)	(0.012+0.139j)	(0.032+0.362j)

Negative Sequence Z-Bus:

(0.008+0.091j)	(0.004+0.043j)	(0.006+0.072j)
(0.004+0.043j)	(0.025+0.282j)	(0.012+0.139j)
(0.006+0.072j)	(0.012+0.139j)	(0.032+0.362j)

Zero Sequence Z-Bus:

(0.024+0.273j)	(0.011+0.13j)	(0.019+0.216j)
(0.011+0.13j)	(0.074+0.845j)	(0.036+0.416j)
(0.019+0.216j)	(0.036+0.416j)	(0.095+1.085j)

In [17]:

```
# Evaluate The Thevenin Set For Fault Calculations
Zth = [zbus0[2,2],zbus1[2,2],zbus2[2,2]]
print("Sequence Impedances at Bus B:",np.around(Zth,3))

# Evaluate Sequence Currents and Fault Voltages for SLG
I012 = flt.phs1g(1,Zth)
Vfault = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly1 = flt.busvolt(0,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly2 = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nSingle Line to Ground:")
ep.cprint(Vrly1,"V",["Relay1 VA:","Relay1 VB:","Relay1 VC:"])
ep.cprint((Vrly1-Vfault)/zl13,"A",["Relay1 IA:","Relay1 IB:","Relay1 IC:"])
ep.cprint(Vrly2,"V",["Relay2 VA:","Relay2 VB:","Relay2 VC:"])
ep.cprint((Vrly2-Vfault)/zl32,"A",["Relay2 IA:","Relay2 IB:","Relay2 IC:"])

# Evaluate Sequence Currents and Fault Voltages for LL
I012 = flt.phs2(1,Zth)
Vfault = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly1 = flt.busvolt(0,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly2 = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nLine to Line:")
ep.cprint(Vrly1,"V",["Relay1 VA:","Relay1 VB:","Relay1 VC:"])
ep.cprint((Vrly1-Vfault)/zl13,"A",["Relay1 IA:","Relay1 IB:","Relay1 IC:"])
ep.cprint(Vrly2,"V",["Relay2 VA:","Relay2 VB:","Relay2 VC:"])
ep.cprint((Vrly2-Vfault)/zl32,"A",["Relay2 IA:","Relay2 IB:","Relay2 IC:"])

# Evaluate Sequence Currents and Fault Voltages for DLG
I012 = flt.phs2g(1,Zth)
Vfault = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly1 = flt.busvolt(0,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly2 = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nDouble Line to Ground:")
ep.cprint(Vrly1,"V",["Relay1 VA:","Relay1 VB:","Relay1 VC:"])
ep.cprint((Vrly1-Vfault)/zl13,"A",["Relay1 IA:","Relay1 IB:","Relay1 IC:"])
ep.cprint(Vrly2,"V",["Relay2 VA:","Relay2 VB:","Relay2 VC:"])
ep.cprint((Vrly2-Vfault)/zl32,"A",["Relay2 IA:","Relay2 IB:","Relay2 IC:"])
```

```
Sequence Impedances at Bus B: [ 0.095+1.085j  0.032+0.362j  0.032+0.362j]

Single Line to Ground:
[['Relay1 VA: 0.617 ∠ 0.0° V']
 ['Relay1 VB: 1.085 ∠ -127.031° V']
 ['Relay1 VC: 1.085 ∠ 127.031° V']]
[['Relay1 IA: 0.898 ∠ -85.0° A']
 ['Relay1 IB: 0.359 ∠ -85.0° A']
 ['Relay1 IC: 0.359 ∠ -85.0° A']]
[['Relay2 VA: 0.88 ∠ -0.0° V']
 ['Relay2 VB: 1.025 ∠ -122.321° V']
 ['Relay2 VC: 1.025 ∠ 122.321° V']]
[['Relay2 IA: 0.998 ∠ -85.0° A']
 ['Relay2 IB: 0.399 ∠ -85.0° A']
 ['Relay2 IC: 0.399 ∠ -85.0° A']]

Line to Line:
[['Relay1 VA: 1.0 ∠ 0.0° V']
 ['Relay1 VB: 0.732 ∠ -133.114° V']
 ['Relay1 VC: 0.732 ∠ 133.114° V']]
[['Relay1 IA: 0.0 ∠ 0.0° A']
 ['Relay1 IB: 0.778 ∠ -175.0° A']
 ['Relay1 IC: 0.778 ∠ 5.0° A']]
[['Relay2 VA: 1.0 ∠ 0.0° V']
 ['Relay2 VB: 0.912 ∠ -123.262° V']
 ['Relay2 VC: 0.912 ∠ 123.262° V']]
[['Relay2 IA: 0.0 ∠ 0.0° A']
 ['Relay2 IB: 0.865 ∠ -175.0° A']
 ['Relay2 IC: 0.865 ∠ 5.0° A']]

Double Line to Ground:
[['Relay1 VA: 1.11 ∠ -0.0° V']
 ['Relay1 VB: 0.617 ∠ -120.0° V']
 ['Relay1 VC: 0.617 ∠ 120.0° V']]
[['Relay1 IA: 0.257 ∠ 95.0° A']
 ['Relay1 IB: 0.898 ∠ 155.0° A']
 ['Relay1 IC: 0.898 ∠ 35.0° A']]
[['Relay2 VA: 1.034 ∠ -0.0° V']
 ['Relay2 VB: 0.88 ∠ -120.0° V']
 ['Relay2 VC: 0.88 ∠ 120.0° V']]
[['Relay2 IA: 0.285 ∠ 95.0° A']
 ['Relay2 IB: 0.998 ∠ 155.0° A']
 ['Relay2 IC: 0.998 ∠ 35.0° A']]
```

In [18]:

```
# Evaluate Sequence Currents and Fault Voltages for SLG
I012 = flt.phs1g(1,Zth,Rf=Rf)
Vfault = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly1 = flt.busvolt(0,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly2 = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("Single Line to Ground:")
ep.cprint(Vrly1,"V",["Relay1 VA:","Relay1 VB:","Relay1 VC:"])
ep.cprint((Vrly1-Vfault)/zl13,"A",["Relay1 IA:","Relay1 IB:","Relay1 IC:"])
ep.cprint(Vrly2,"V",["Relay2 VA:","Relay2 VB:","Relay2 VC:"])
ep.cprint((Vrly2-Vfault)/zl32,"A",["Relay2 IA:","Relay2 IB:","Relay2 IC:"])

# Evaluate Sequence Currents and Fault Voltages for LL
I012 = flt.phs2(1,Zth,Rf=Rf)
Vfault = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly1 = flt.busvolt(0,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly2 = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nLine to Line:")
ep.cprint(Vrly1,"V",["Relay1 VA:","Relay1 VB:","Relay1 VC:"])
ep.cprint((Vrly1-Vfault)/zl13,"A",["Relay1 IA:","Relay1 IB:","Relay1 IC:"])
ep.cprint(Vrly2,"V",["Relay2 VA:","Relay2 VB:","Relay2 VC:"])
ep.cprint((Vrly2-Vfault)/zl32,"A",["Relay2 IA:","Relay2 IB:","Relay2 IC:"])

# Evaluate Sequence Currents and Fault Voltages for DLG
I012 = flt.phs2g(1,Zth,Rf=Rf)
Vfault = flt.busvolt(2,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly1 = flt.busvolt(0,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
Vrly2 = flt.busvolt(1,2,1,zbus0,zbus1,zbus2,I012,sequence=False)
print("\nDouble Line to Ground:")
ep.cprint(Vrly1,"V",["Relay1 VA:","Relay1 VB:","Relay1 VC:"])
ep.cprint((Vrly1-Vfault)/zl13,"A",["Relay1 IA:","Relay1 IB:","Relay1 IC:"])
ep.cprint(Vrly2,"V",["Relay2 VA:","Relay2 VB:","Relay2 VC:"])
ep.cprint((Vrly2-Vfault)/zl32,"A",["Relay2 IA:","Relay2 IB:","Relay2 IC:"])
```

```
Single Line to Ground:
[['Relay1 VA: 0.863 ∠ -11.493° V']
 ['Relay1 VB: 1.091 ∠ -121.001° V']
 ['Relay1 VC: 0.975 ∠ 125.167° V']]
[['Relay1 IA: 0.541 ∠ -36.897° A']
 ['Relay1 IB: 0.217 ∠ -36.897° A']
 ['Relay1 IC: 0.217 ∠ -36.897° A']]
[['Relay2 VA: 0.953 ∠ -3.231° V']
 ['Relay2 VB: 1.028 ∠ -120.332° V']
 ['Relay2 VC: 0.991 ∠ 121.586° V']]
[['Relay2 IA: 0.602 ∠ -36.897° A']
 ['Relay2 IB: 0.241 ∠ -36.897° A']
 ['Relay2 IC: 0.241 ∠ -36.897° A']]

Line to Line:
[['Relay1 VA: 1.0 ∠ 0.0° V']
 ['Relay1 VB: 0.96 ∠ -132.763° V']
 ['Relay1 VC: 0.786 ∠ 116.27° V']]
[['Relay1 IA: 0.0 ∠ 0.0° A']
 ['Relay1 IB: 0.519 ∠ -131.643° A']
 ['Relay1 IC: 0.519 ∠ 48.357° A']]
[['Relay2 VA: 1.0 ∠ 0.0° V']
 ['Relay2 VB: 0.982 ∠ -123.87° V']
 ['Relay2 VC: 0.933 ∠ 119.018° V']]
[['Relay2 IA: 0.0 ∠ 0.0° A']
 ['Relay2 IB: 0.577 ∠ -131.643° A']
 ['Relay2 IC: 0.577 ∠ 48.357° A']]

Double Line to Ground:
[['Relay1 VA: 1.029 ∠ 2.42° V']
 ['Relay1 VB: 0.642 ∠ -134.511° V']
 ['Relay1 VC: 0.758 ∠ 126.425° V']]
[['Relay1 IA: 0.122 ∠ 151.806° A']
 ['Relay1 IB: 0.963 ∠ 178.046° A']
 ['Relay1 IC: 0.611 ∠ 16.005° A']]
[['Relay2 VA: 1.009 ∠ 0.771° V']
 ['Relay2 VB: 0.883 ∠ -123.264° V']
 ['Relay2 VC: 0.923 ∠ 121.646° V']]
[['Relay2 IA: 0.135 ∠ 151.806° A']
 ['Relay2 IB: 1.07 ∠ 178.046° A']
 ['Relay2 IC: 0.679 ∠ 16.005° A']]
```

In [ ]:

```
1
```