

## ECE 524

## Exam 1

## Summer 2019

### EXAMINATION RULES

1. This is an open-book/open-note take-home exam.
2. I can e-mail a MathCAD file with the exam problems to you if you would like a copy.
3. Do your own work on this examination. You are on your honor. Therefore, you will neither give nor receive aid on this examination, except from the *course* instructor. If you violate this trust, you will receive the grade of zero for this examination.
4. Show all of your work! Make it neat. *No* partial credit will be given if I can not easily follow your work.
5. You have 3 days to complete the exam the exam from the time you receive it from your proctor.
6. Please read and sign the following statement when you finish the exam:

I certify that I have neither given nor have I received any help on this examination, except from the course instructor.

SIGNED: \_\_\_\_\_

PRINTED NAME: \_\_\_\_\_

DATE: \_\_\_\_\_

1. \_\_\_\_\_/40 pts

2. \_\_\_\_\_/20 pts

3. \_\_\_\_\_/40 pts

Total: \_\_\_\_\_/100 pts

1. (40 pts) Consider the system shown below. The power ratings given are three phase ratings, and voltages listed are line to line.

A. Create a system equivalent for capacitor switching studies. Explain your reasoning in developing the model. Describe how you would validate this model to ensure accuracy.

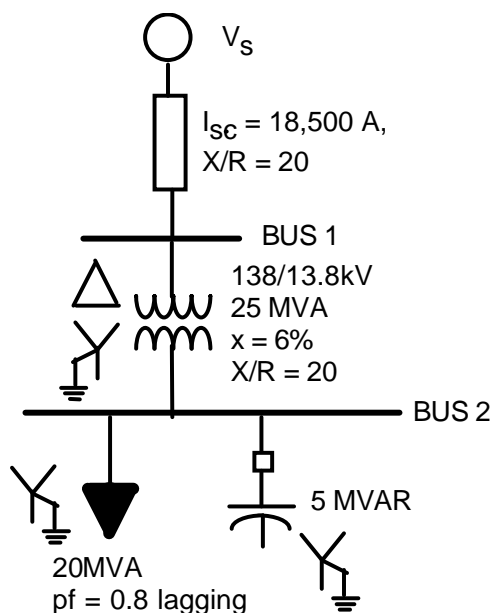
Build this model in your transient program. Perform a steady-state analysis and adjust the source voltage so the voltage at the capacitor bus is 1.0pu with the capacitor in the system. Verify this with your transient simulation program.

B. Describe (with sketches as needed) what happens when the breaker for the capacitor bank is opened. Back this up with simulation results.

C. Estimate the worst case current on energization of the capacitor bank. Does the 60Hz term need to be considered in this calculation (why or why not)? Again, confirm this with simulation results. Compare simulation results with and without the load and the resistances of the source and transformer included and comment on the impact on the response.

D. Determine the worst voltage seen by the load due to this worst case capacitor switching transient from part (C) through simulation.

E. Propose options to reduce this transient.



2. (20 pts). Answer the following:

- A. Explain what causes overvoltage conditions in transient recovery voltage. What is the voltage we are concerned about? Describe with diagrams as needed. Explain.
- B. Once you know the worst case transient recovery voltage amplitude, how will you use that information? Does natural frequency matter? Why?
- C. Describe corrective actions that can be used to reduce the impact if the transient recovery voltage transient is unacceptable. Briefly describe how these corrective actions work.
- D. Does the angle between the voltage and breaker current prior to transient impact the TRV transient response? In what way?

3. (40 pts) You are given a 345 kV transmission system that consists of 3 transmission line segments, with intermediate buses separating them (see figure below). Each of the transmission line segments has the following characteristics (calculated at 60Hz).

$$R_0 := 0.3112 \frac{\text{ohm}}{\text{mi}}$$

$$R_1 := 0.0381 \frac{\text{ohm}}{\text{mi}}$$

$$R_2 := 0.0381 \frac{\text{ohm}}{\text{mi}}$$

$$Z_{c0} := 654.86 \text{ohm}$$

$$Z_{c1} := 256.35 \text{ohm}$$

$$Z_{c2} := 256.35 \text{ohm}$$

$$\nu_0 := 1.2254 \cdot 10^5 \cdot \frac{\text{mi}}{\text{s}}$$

$$\nu_1 := 1.8213 \cdot 10^5 \cdot \frac{\text{mi}}{\text{s}}$$

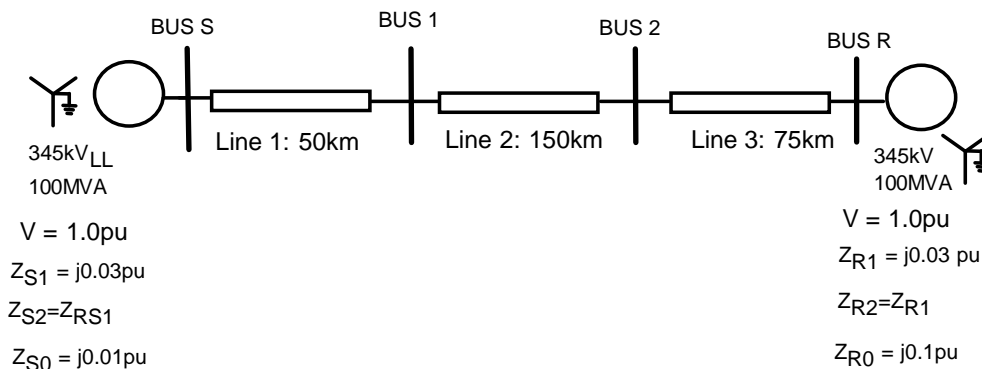
$$\nu_2 := 1.8213 \cdot 10^5 \cdot \frac{\text{mi}}{\text{s}}$$

A. The mode 1 and mode 2 terms are identical. Explain what this tells you about the transmission line. What underlying assumptions have been made and what limitations should be considered for applying this model.

B. Calculate the ABC domain  $R'$ ,  $L'$  and  $C'$  matrices per mile.

C. What do the modes 0, 1 and 2 represent? Where do the signals they represent travel?

D. A single line diagram for the system is shown below. Implement a model of this system, each line has the characteristics above. Use the appropriate travelling wave model. Describe how you would validate your model before starting transient studies, and suggest a time step for transient simulation. Use coupled RL (sequence data input) for the source impedances.



E. Suppose a three phase fault occurs 60% of the way from Bus 1 to Bus 2 (set both sources to be at 1.0 pu at an angle of 0 degrees). Do a simple analysis for each step and then simulate.

- (1) How long will it take the transient to reach Bus 1? How long will it take to reach Bus 2?
- (2) What is the voltage reflection coefficient seen by the voltage when it reaches Bus 1? Based on that, what would expect the voltage to look like at that bus?
- (3) How would your answer to (2) change if the line between buses BUS S and BUS 1 were open?
- (4) Calculate the initial surge current at the fault location.
- (5) How long will it take the initial surge current to reach BUS 1 and BUS 2? For case (3) currents look like at BUS 1 and BUS 2 look like when those surges arrive?

# Joe Stanley

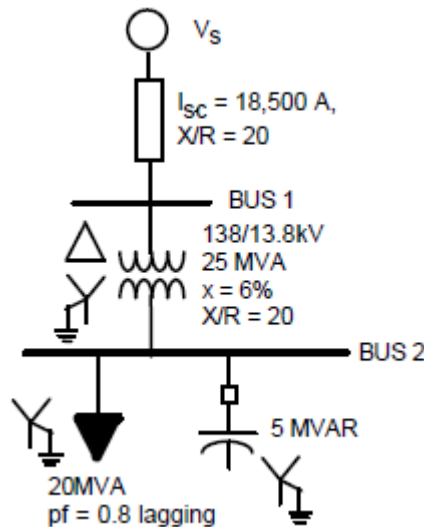
ECE 524 - EXAM 1 (Midterm)

In [74]:

```
1  # Import Libraries
2  import numpy as np
3  import matplotlib.pyplot as plt
4  import eepower as eep
5  from eepower import p,n,u,m,k,M
6  from scipy.optimize import fsolve
7
8  # Define Loaded Voltage Source Function
9  def loadedsource(Vload,Zload,Zline,Zsource=None,Zload2=None):
10     """
11     loadedsource Function
12
13     Evaluates the terminal voltage of a voltage source given
14     a specified load impedance and line impedance. Can also
15     find the internal voltage of a generation source given the
16     internal source impedance.
17
18     Parameters
19     -----
20     Vload:      complex
21                 The desired voltage across the load impedance.
22     Zload:      complex
23                 The load impedance in ohms.
24     Zline:      complex
25                 The line impedance in ohms.
26     Zsource:    complex, optional
27                 The source internal impedance in ohms,
28                 default=None.
29     Zload2:     complex, optional
30                 A secondary load impedance to be included in
31                 parallel, default=None.
32
33     Returns
34     -----
35     Vt:         complex
36                 The terminal voltage of the source.
37     Iload:      complex
38                 The load current in amps.
39     Ea:         complex, optional
40                 The internal source voltage.
41     """
42     # Evaluate Load Current
43     if Zload2 != None:
44         Zload = eep.parallelz(Zload,Zload2)
45     Iload = Vload/Zload
46     # Evaluate Voltage Drop Down Line
47     Vdrop_line = Iload * Zline
48     Vt = Vload + Vdrop_line
49     # If Given, Evaluate Source Vdrop
50     if Zsource != None:
51         Vdrop_source = Iload * Zsource
52         Ea = Vt + Vdrop_source
53     return(Vt,Iload,Ea)
54     # Return The Terminal Voltage
55     return(Vt,Iload)
```

## Problem 1:

Consider the system shown below. The power ratings given are three phase ratings, and voltages listed are line to line.



A) Create a system equivalent for capacitor switching studies. Explain your reasoning in developing the model. Describe how you would validate this model to ensure accuracy. Build this model in your transient program. Perform a steady-state analysis and adjust the source voltage so the voltage at the capacitor bus is 1.0pu with the capacitor in the system. Verify this with your transient simulation program.

- Calculations to demonstrate the process related to this simplification in the code section following these responses.
- I have so chosen to simplify the system by combining the transformer and source impedances into one lumped impedance. The load should still be maintained as a discrete element.
- As might have been guessed, the source voltage must be greater than the bus voltage.
- Simulation included as Prob1\_PA

B) Describe (with sketches as needed) what happens when the breaker for the capacitor bank is opened. Back this up with simulation results.

- Opening the capacitor bank's breaker will cause transient to begin. The transient will cause a high-frequency ringing on the system that will slowly damp over time. The capacitor helps maintain voltage stability and reliability on the bus, so removing the cap will inevitably reduce these characteristics.
- Simulation included as Prob1\_PB

C) Estimate the worst case current on energization of the capacitor bank. Does the 60Hz term need to be considered in this calculation (why or why not)? Again, confirm this with simulation results. Compare simulation results with and without the load and the resistances of the source and transformer included and comment on the impact on the response.

- To estimate this worst case current, I'm neglecting all inductance between the source and capacitance. I'm also assuming that the capacitor starts at 0 volts, and we're using the peak voltage.

- In this case, I'm using the 60Hz voltage, only out of convenience, it does play a significant role, as it's voltage sets the voltage that the capacitor is trying to reach. I am neglecting this fact for my approximation, as such, it should be noted that my approximation is quite crude.
- Simulation Included as Prob1\_PC

**D) Determine the worst voltage seen by the load due to this worst case capacitor switching transient from part (C) through simulation.**

- From simulation, the resulting worst-case voltage is approximately 55kV, Line-Neutral.

**E) Propose options to reduce this transient.**

- Break the cap-bank into smaller sub-banks which can be switched independently.
- Introduce a small resistance or inductance between the bus and the cap bank to reduce transient action. Note that the inductance would need to be tuned as an appropriate filter.



In [42]:

```
1  # Define Givens
2  Vs = 138*k
3  ISC = 18500
4  XoR = 20
5  xfm_n = 138/13.8
6  xfm_rat = 25*M
7  xfm_x = 6/100
8  xfm_xor = 20
9  load = 20*M
10 load_pf = 0.8 #lagging
11 cbank = 5*M
12 # Define PU Bases
13 Sbase = xfm_rat
14 Vb1 = 138*k
15 Vb2 = 13.8*k
16 Zb = eep.zpu(Sbase,VLL=Vb2)
17
18 # Evaluate Source Impedance
19 SCMVA = ISC*Vs
20 Zsrc = eep.zsource(SCMVA,Vs,XoR,Sbase=Sbase)
21 print("SRC Z:\t",np.round(Zsrc,6),"pu-Ω\tR:",round(Zsrc.real*Zb,4),"Ω\tL:",r
22 # Evaluate Transformer Impedance
23 r,x = eep.zdecompose(xfm_x,xfm_xor)
24 Zxfm = r+1j*x
25 print("XFM Z:\t",np.round(Zxfm,6),"pu-Ω\tR:",round(Zxfm.real*Zb,4),"Ω\tL:",r
26 # Break the Load into Resistance/Reactance
27 ##### NOTE ##### Load is divided by three to account for 3-phs value being pro
28 r,x = eep.powerimpedance(load/3,Vb2,load_pf)
29 Zload = r+1j*x
30 print("LOAD Z:\t",np.round(Zload/Zb,6),"pu-Ω\t\tR:",round(Zload.real*Zb,4),"
31 print() # Insert Gap
32
33 # Evaluate Capacitance Value
34 Cval = eep.farads(cbank,Vb2)
35 print("Capacitor Value:",Cval/u,"μF")
36 print()
37
38 # Find the source voltage to sustain 1.0pu-V on the cap bank
39 Vsln,Ild = loadedsource(1.0,Zload/Zb,Zsrc+Zxfm,Zload2=eep.phasorz(C=Cval)/Zb
40 Vsll = eep.phaseline(VLN = Vsln)
41 eep.cprint(Vsll,"pu-V","Required Source Voltage:")
42 eep.cprint(Vsll*Vb2/np.sqrt(2),"V","Required Source Voltage:")
43
44 # Estimate the Worst-Case Charging Current
45 Iworst = Vsln*Vb2 / (Zsrc.real*Zb + Zxfm.real*Zb)
46 eep.cprint(Iworst/k,"kA","Worst-Case Charging Current:")
```

SRC Z:	(0.000489+0.00978j) pu-Ω	R: 0.0037 Ω	L: 0.1979 mH
XFM Z:	(0.002996+0.059925j) pu-Ω	R: 0.0228 Ω	L: 1.2124 mH
LOAD Z:	(4.6875+6.25j) pu-Ω	R: 272.0055 Ω	L: 157.8618 mH

Capacitor Value: 69.64351987147981 μF

Required Source Voltage: 1.721 ∠ 0.0° pu-V

Required Source Voltage: 16791.294 ∠ 0.0° V

Worst-Case Charging Current: 516.398 ∠ 0.328° kA

## Problem 2:

**A) Explain what causes overvoltage conditions in transient recovery voltage. What is the voltage we are concerned about? Describe with diagrams as needed. Explain.**

- Transient Recovery Voltages are caused by inductive properties of the power system. When a breaker opens, the current is interrupted, but inductors can't instantly allow current flow to cease. As a result, the inductors raise enormous amounts of voltage as a way to compensate. It is this "recovery" voltage that is known as a TRV. This TRV amplitude and its accompanying rate of rise are both factors that need to be considered for the effectiveness and safety of electrical breakers. In particular, the voltage across the breaker contacts is the one that we're most concerned about. If this voltage exceeds the breaker's capacity, it will restrike until the transient has subsided. This restrike is extremely damaging to breaker contacts, and can be threatening to the safety of any nearby personnel. As such, it is of great concern.

**B) Once you know the worst case transient recovery voltage amplitude, how will you use that information? Does natural frequency matter? Why?**

- Such information can be used to rate circuit breakers and equipment to withstand the TRV.
- Natural frequency does matter. It can be very useful in applying TRV mitigation techniques such as filtering. If the natural frequency is considerably greater than the 60Hz frequency or any significant harmonics, it can be used to apply a filter that appears as a dead-short at the natural frequency. This would allow for effective current dissipation during TRV conditions.

**C) Describe corrective actions that can be used to reduce the impact if the transient recovery voltage transient is unacceptable. Briefly describe how these corrective actions work.**

- As mentioned previously, applying filters tuned to the natural frequency can be a highly effective mitigation technique as they will allow current dissipation into a safe route.
- Additionally, since TRV is caused primarily by inductance in a circuit path. Applying capacitors in varying ways may also be beneficial by providing a current route for the TRV.
- As a final mention, switching in resistors at the same time as the breaker being opened may be of particular use by providing a dissipation path.

**D) Does the angle between the voltage and breaker current prior to transient impact the TRV transient response? In what way?**

- The angle does play a particular role in transient response as it dictates the additive point where transient voltage is applied to the 60Hz component. If the current and voltage are in phase, the overall voltage (60Hz comp. and TRV comp.) will serve to be greater as it will be a summation of their impacts.

## Problem 3:

You are given a 345 kV transmission system that consists of 3 transmission line segments, with intermediate buses separating them (see figure below). Each of the transmission line segments has the following characteristics (calculated at 60Hz).

$$R_0 := 0.3112 \frac{\text{ohm}}{\text{mi}}$$

$$R_1 := 0.0381 \frac{\text{ohm}}{\text{mi}}$$

$$R_2 := 0.0381 \frac{\text{ohm}}{\text{mi}}$$

$$Z_{c0} := 654.86 \text{ohm}$$

$$Z_{c1} := 256.35 \text{ohm}$$

$$Z_{c2} := 256.35 \text{ohm}$$

$$v_0 := 1.2254 \cdot 10^5 \frac{\text{mi}}{\text{s}}$$

$$v_1 := 1.8213 \cdot 10^5 \frac{\text{mi}}{\text{s}}$$

$$v_2 := 1.8213 \cdot 10^5 \frac{\text{mi}}{\text{s}}$$

A) The mode 1 and mode 2 terms are identical. Explain what this tells you about the transmission line. What underlying assumptions have been made and what limitations should be considered for applying this model.

- Identifying mode 1 as being equal to mode 2 informs me that the three conductors are equally transposed, meaning that they have swapped positions enough that no one line shows features that significantly differentiate it from the others.
- The underlying assumptions to support this are that the lines themselves will carry the same characteristics over their entire length such that they do not vary resistive, capacitive, or inductive properties for their entire length. The supporting pole structure should remain consistent along the entire length of the line.

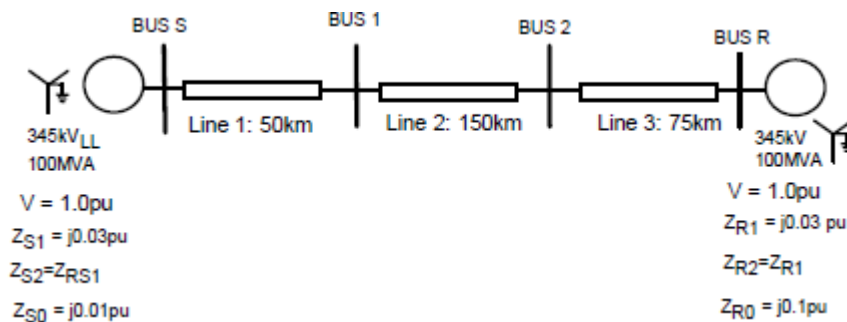
B) Calculate the ABC domain R', L' and C' matrices per mile.

- Calculations Shown in Code Cell below.

C) What do the modes 0, 1 and 2 represent? Where do the signals they represent travel?

- Mode 0 represents what is commonly known as the "ground mode", its related signals travel through the ground return.
- Modes 1 and 2 represent "line modes" as their signals travel through the transmission lines themselves.

D) A single line diagram for the system is shown below. Implement a model of this system, each line has the characteristics above. Use the appropriate travelling wave model. Describe how you would validate your model before starting transient studies, and suggest a time step for transient simulation. Use coupled RL (sequence data input) for the source impedances.



- Model validation would come from a process of cross-validating the model in a phasor-domain simulator (something like PowerWorld) to an electromagnetic transients program (ATP/ATPDraw). Validating that the steady-state performance is equal or nearly equivalent between the two modeling platforms would illustrate model validity.

- Given the signal propagation velocity ( $v$ ) being at a maximum of  $1.8213e5$  (mi/s), it might be sensible to desire collecting distance traveled to the 10th of a mile, at a sampling rate of 20 samples/cycle. This means that a multiple of 200 must be combined with the propagation velocity. A resulting  $3.6526e7$  samples/second results in a delta-T of  $2.74529e-8$ . Rounding this result down for sake of simplicity provides a value of  $2.7e-8$ .
- Model included as Prob3\_PD

**E) Suppose a three phase fault occurs 60% of the way from Bus 1 to Bus 2 (set both sources to be at 1.0 pu at an angle of 0 degrees). Do a simple analysis for each step and then simulate.**

1. How long will it take the transient to reach Bus 1? How long will it take to reach Bus 2?
  - Numerical results calculated in cell below.
2. What is the voltage reflection coefficient seen by the voltage when it reaches Bus 1? Based on that, what would expect the voltage to look like at that that bus?
  - Based on the fact that all lines share the same  $Z_c$ , it is safe to say that the reflection coefficient (for voltage) at BUS 1 will be 0 (as demonstrated in formula below).
3. How would your answer to (2) change if the line between buses BUS S and BUS 1 were open?
  - If the line between BUS S and BUS 1 was open, the resultant coefficient would be 1 as noted from the SEL presentation. Thus the voltage should see a full step change ramping upwards.
4. Calculate the initial surge current at the fault location.
  - Numerical results calculated in cell below.
5. How long will it take the initial surge current to reach BUS 1 and BUS 2? For case (3) currents look like at BUS 1 and BUS 2 look like when those surges arrive?
  - It will take the current approximately the same ammount of time to reach BUS 1/2.
  - For case (3) the currents will see a -1 coefficient impact, so they will reduce by that ammount.

In [96]:

```
1 # Part B
2
3 # Define Ti and Rp
4 Ti = np.asmatrix(np.array( [[1,np.sqrt(2),0],
5                             [1,-1/np.sqrt(2),np.sqrt(3/2)],
6                             [1,-1/np.sqrt(2),-np.sqrt(3/2)]])) * 1/np.sqrt(3)
7 Rp = np.asmatrix(np.array([[0,0,1],
8                             [1,0,0],
9                             [0,1,0]]))
10 def modaltoabc(array):
11     matrix = np.asmatrix(array)
12     return(Ti*matrix*Ti**,-1)
13 def modalcl(zo,vo):
14     def equations(data):
15         C,L = data
16         Z = np.sqrt(L/C)-zo
17         V = 1/np.sqrt(L*C)-vo
18         return(Z,V)
19     C,L = fsolve(equations, (10*n,5*m))
20     return(C,L)
21 # Define and Evaluate Modal Components
22 R0, R1, R2 = 0.3112, 0.0381, 0.0381
23 C0,L0 = modalcl(654.86,1.2254*10**5)
24 C1,L1 = modalcl(256.35,1.8213*10**5)
25 C2,L2 = modalcl(256.35,1.8213*10**5)
26 Rmod = np.array([[R0,0,0],
27                  [0,R1,0],
28                  [0,0,R2]])
29 Cmod = np.array([[C0,0,0],
30                  [0,C1,0],
31                  [0,0,C2]])
32 Lmod = np.array([[L0,0,0],
33                  [0,L1,0],
34                  [0,0,L2]])
35 for i,arr in enumerate([Rmod,Cmod,Lmod]):
36     nm = [["R",1,"Ω/mi"],["C",n,"nF/mi"],["L",m,"mH/mi"]]
37     print("Modal Form (" + nm[i][0] + "mod):\n",arr/nm[i][1],nm[i][2])
38     print("ABC-Domain (" + nm[i][0] + "):\n",modaltoabc(arr)/nm[i][1],nm[i][2])
```

Modal Form (Rmod):

```
[[ 0.3112  0.      0.      ]
 [ 0.      0.0381  0.      ]
 [ 0.      0.      0.0381]] Ω/mi
```

ABC-Domain (R'):

```
[[ 0.12913333  0.09103333  0.09103333]
 [ 0.09103333  0.12913333  0.09103333]
 [ 0.09103333  0.09103333  0.12913333]] Ω/mi
```

Modal Form (Cmod):

```
[[ 12.46159579  0.      0.      ]
 [ 0.      21.41830953  0.      ]
 [ 0.      0.      21.41830953]] nF/mi
```

ABC-Domain (C'):

```
[[ 18.43273829 -2.98557125 -2.98557125]
 [-2.98557125 18.43273829 -2.98557125]
 [-2.98557125 -2.98557125 18.43273829]] nF/mi
```

Modal Form (Lmod):

```
[[ 5.34405092  0.      0.      ]
```

```

[ 0.          1.40751112  0.          ]
[ 0.          0.          1.40751112]] mH/mi
ABC-Domain (L'):
[[ 2.71969105  1.31217993  1.31217993]
 [ 1.31217993  2.71969105  1.31217993]
 [ 1.31217993  1.31217993  2.71969105]] mH/mi

```

In [106]:

```

1  # Part D
2
3  # 1)
4  dist = 150 #km
5  dist *= 0.621371 #mi
6  v0 = 1.2254e5
7  v12 = 1.8213e5 #mi/sec
8  floc_1 = dist * 0.6
9  floc_2 = dist * 0.4
10 print("1) Time to travel from fault to Bus 1:",floc_1/(v12*u),"μsec")
11 print("    Time to travel from fault to Bus 2:",floc_2/(v12*u),"μsec")
12
13 # 2)
14 zc12 = 256.35
15 Zc = zc12
16 Zt = zc12
17 Vcoef = (Zt-Zc)/(Zt+Zc)
18 print("2) Voltage Reflection Coefficient:",Vcoef)
19
20 # 4)
21 vfault = 345*k
22 ifault = vfault/zc12
23 print("4) Initial Surge Current:",round(ifault,2),"A")

```

```

1) Time to travel from fault to Bus 1: 307.05205073299294 μsec
   Time to travel from fault to Bus 2: 204.70136715532863 μsec
2) Voltage Reflection Coefficient: 0.0
4) Initial Surge Current: 1345.82 A

```

In [ ]:

1

In [ ]:

1