EE 374 TERM PROJECT REPORT

Tunahan Aktaş

2231157

In Phase-1, we take the data from text file to our work space. It was easy since we knew which line corresponds to which line (number of circuits 2nd line, length of the line 8th line). Number of lines dependent on the number of circuits. We first checked number of circuits. If it is 1, we assign -1 (null) to second circuits coordinates. Then, we read the data line by line until "-999" string and store them on workspace with related variable type. We are also asked to consider line name typos. We do this by implementing this sentence in MATLAB's language: "If the string in 10th line of the input mismatches with one of the conductor names in our library, ask for another name from user until the given name matches with the conductor names in our library."

Phase-2 was the hardest one. Let's start with our GMR calculation approach. For a single conductor per phase, library gives us line specific GMR value, whose coordinates are at the centre of the phase lines. For more than one conductor in per phase (bundled case), we are given that the bundles form a regular polygon.

We explain our approach on Figure 1. We assumed that there is always one conductor on possitive x axis (angle(A) = 0). Let's look at an arbitrary consecutive conductor, which forms a triangle with the centre of the polygon; D1-D2-O. We know that this is an isosceles triangle and we can find angle θ using the properties of cycle:

$$\theta = \frac{\pi}{n_{bundle}}$$

We know $D_{12}/2$ (half of the distence between conductors), so, we can find length of A using simple trigonometry:

$$|A| = \frac{D_{12}}{2 * \sin(\theta)}$$

As we state before, We assumed that there is always one conductor on possitive x axis (angle(A) = 0). Then, starting from 0 angle and increasing the angle with 2θ degrees for n_{bundle} steps, (our step size is 2θ degree) we can find all of the conductors in a bundle.

For the sake of simpicity, we use complex plane to represent conductors' coordinates. Imaginary axis corresponds to y-axis. We use Euler's formula to shift A. Therefore, we did not need 2 matrices to hold x and y values. We used one compex valued matrix to hold all conductors' coordinate in a bundle (1 bundle → 1 matrix).

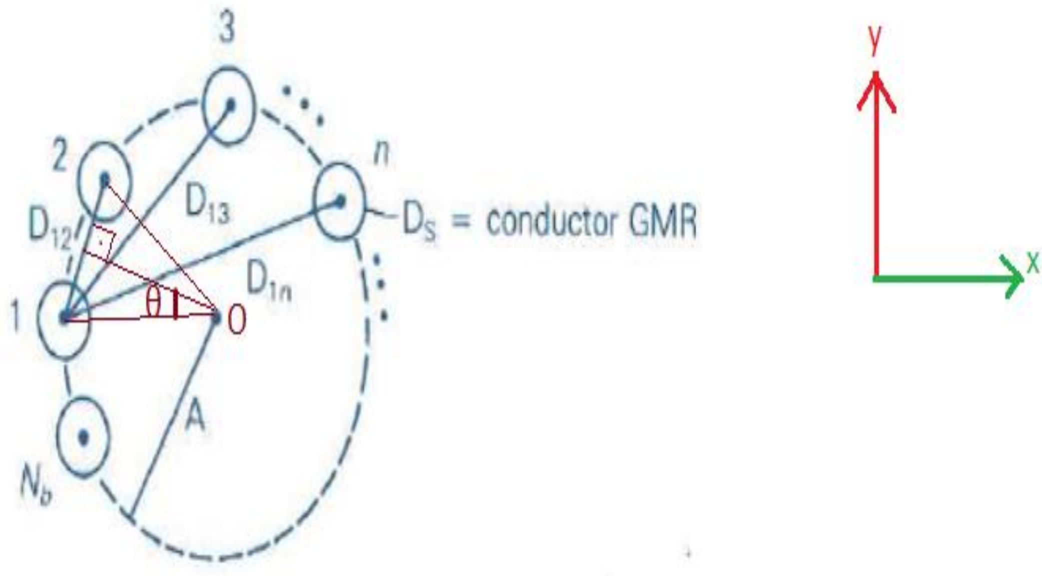

Figure 1: Shows variables for analyzing bundle GMR calculation.

We have all of the conductors, we choose one and find all other conductor's distances to selected one (D_{12}, D_{13}, .. D_{1n}). Now, we can find GMR by using this distences and line specific GMR that we found in the library (call Ds). We use this formula for calculating inductance.

$$GMR = \sqrt[n_{bundle}]{D_s . D_{12} . D_{13} . \dots \dots \dots . D_{1n}}$$

For capacitance, we use same formula but only D_s changes to outer radious of the line, which can again be found on library.

$$D_{SC}^{b} = \sqrt[n_{bundle}]{r_o . D_{12} . D_{13} . \dots \dots . . D_{1n}}$$

For one circuit case, calculation of GMD is straightforward:

$$GMD = \sqrt[3]{D_{AB} . D_{BC} . D_{CA}}$$

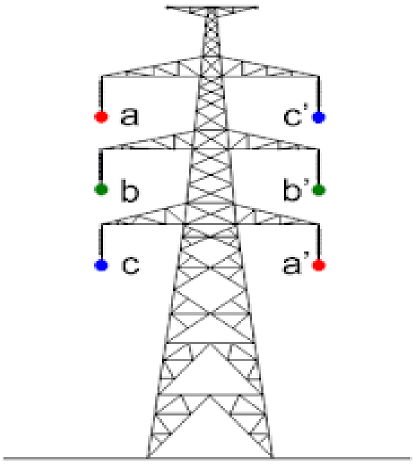

Fig-A(i): Double Circuit line

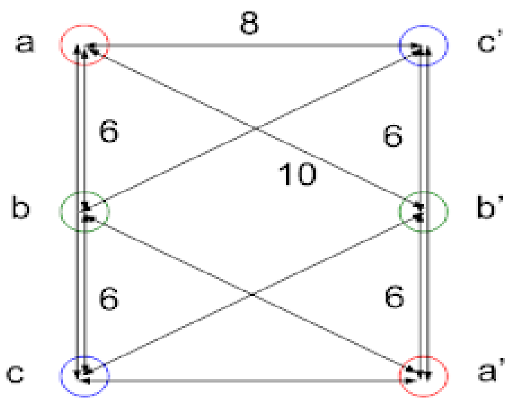

Fig-A(ii): Distances between the phase conductors of Double Circuits

For calculating GMD in two circuit case, all the distances between the phase conductors are identified. In Fig-A(ii) all the distances between the phases are shown. For example a-b, a-c, a-c', a-b', c-b', c-a' etc.. There are 12 possible distances between conductors of phases as shown. It should be noted that for calculation of GMD the distances a-a', b-b' and c-c' are not taken.

$$GMD = \sqrt[12]{(D_{ab} \, . D_{ab'} \, . D_{bc} \, . D_{bc'} . D_{ca} \, . D_{c'a} . \; D_{a'b} \, . D_{a'b'} \, . D_{b'c} \, . D_{b'c'} \, . D_{c'a} \, . D_{c'a'})}$$

To calculate the capacitance with groun effect, the negative charge of the earth can be replaced by an equivalent charge of an image conductor with the same radius as the overhead conductor, lying just below the overhead conductor (Figure 2)

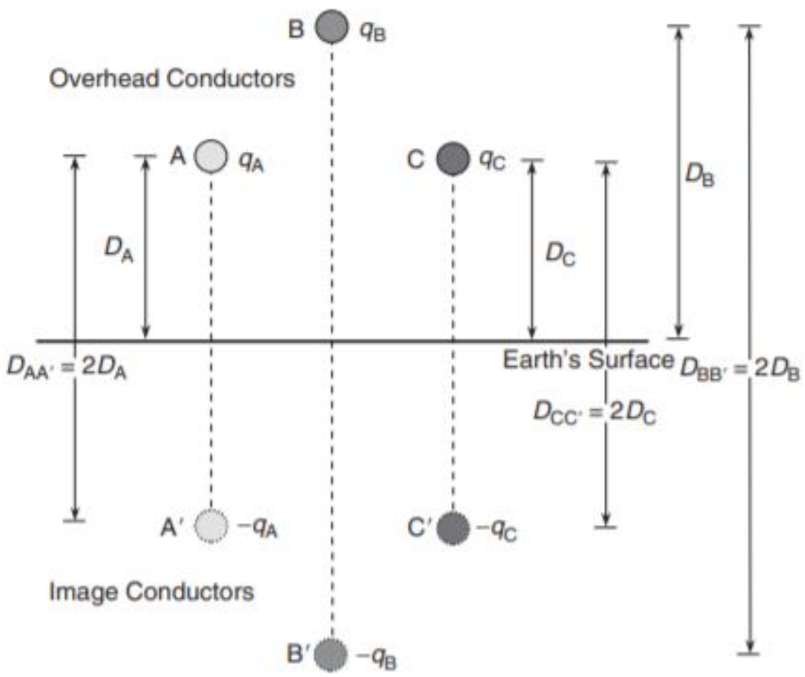

Figure 2: Imaginary and real conductors for ground effect in capacitance calculations.

Then, it is easy to find series line inductance per meter and shunt line capacitance per meter:

$$L = 2.10^{-7}.\ln\left(\frac{GMD}{GMR}\right) \quad \frac{H}{m}\ per\ phase$$

$$C_n = \frac{2.\Omega.k}{\ln\left(\frac{GMD}{D_{sC}}\right) - \ln\left(\frac{\sqrt[3]{D_{AB'}\ .\ D_{BC'}\ .D_{CA'}}}{\sqrt[3]{D_{AA'}\ .\ D_{BB'}\ .D_{CC'}}}\right)} \quad \frac{F}{m}\ per\ phase$$

Where k = $8.85*10^{-12}$. For two circuit case, for calculating earth effect, we have similar relation with GMD calculation.

Now, we are ready to test our function. We will use two examples from Grainger's book. The first one is Example 3.5 at page 62:

Example 3.5 Each conductor of the bundled-conductor line shown in Fig. 3.14 is ACSR, 1,272,000-cmil *Pheasant*. Find the inductive reactance in ohms per km (and per mile) per phase for $d = 45$ cm. Also find the per-unit series reactance of the line if its length is 160 km and base is 100 MVA, 345 kV.

SOLUTION From Table A.1 $D_s = 0.0466$ ft, and we multiply feet by 0.3048 to convert to meters.

$$D_s^b = \sqrt{0.0466 \times 0.3048 \times 0.45} = \boxed{0.080 \text{ m}}$$

$$D_{eq} = \sqrt[3]{8 \times 8 \times 16} = \boxed{10.08 \text{ m}}$$

$$X_L = 2\pi 60 \times 2 \times 10^{-7} \times 10^3 \ln \frac{10.08}{0.08}$$

$$= \boxed{0.365\ \Omega/\text{km per phase}}$$

$$(0.365 \times 1.609 = 0.587\ \Omega/\text{mi per phase})$$

$$\text{Base } Z = \frac{(345)^2}{100} = 1190\ \Omega$$

$$X = \frac{0.365 \times 160}{1190} = 0.049 \text{ per unit}$$

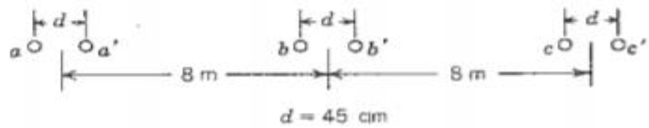

Figure 3.14 Spacing of conductors of a bundled-conductor line.

Note that we can create an input text file in our project's format since all the data we need is avaliable on the question. If we create such file and give to our function, it will also show that our first phase works well. We create such file and for testing purposes, we modify our outputs so that we can see GMD, GMR and D_s values. Our outputs are:

```
ans =

   0.023332443500000   Series resistance
   0.364691522803109   X_L value at 60 Hz
   0.079947832991270   GMR value
   0.088871423978690   D_sc value
  10.079368399158984   GMD value
```

If we compare real resuts and our outputs, it seems we are good to go. The second example we use to test is Example 4.3 at page 85.

Example 4.3 Find the capacitive reactance to neutral of the line described Example 3.5 in ohm-kilometers (and in ohm-miles) per phase.

SOLUTION Computed from the diameter given in Table A.1

$$r = \frac{1.382 \times 0.3048}{2 \times 12} = 0.01755 \text{ m}$$

$$D_{sC}^{b} = \sqrt{0.01755 \times 0.45} = 0.0889 \text{ m}$$

$$D_{eq} = \sqrt[3]{8 \times 8 \times 16} = 10.08 \text{ m}$$

$$C_n = \frac{2\pi \times 8.85 \times 10^{-12}}{\ln (10.08/0.0889)} = 11.754 \times 10^{-12} \text{ F/m}$$

$$X_C = \frac{10^{12} \times 10^{-3}}{2\pi 60 \times 11.754} = \boxed{0.2257 \times 10^{6}\ \Omega\cdot\text{km per phase to neutral}}$$

$$\left(X_C = \frac{0.2257 \times 10^{6}}{1.609} = 0.1403 \times 10^{6}\ \Omega\cdot\text{mi per phase to neutral}\right)$$

Since it uses Example 3.5's data, we only show X_C value of the output. Others are same. Note that our function calculates suceptance reactance. We have to inverse it to get capacitive reactance:

ans =

2.255835948851256e+05

Now, let's test bonus part and two circuit case. We will use Input_file_example1.txt under odtuclass – Term Project file. Expected outputs are (bonus part, last two line, not included):

[0.0077

0.0965

1.1598e-05

-1

-1]

Form: [R; X; B; X_Bonus; B_Bonus]

Our function's outputs (original results. We will compare every result with this one):

ans =

0.007743823625000

0.096497366214921

0.000011598213856

0.096496912799382

0.000011598269400

If we increase length, nothing will change for this part because we are finding everything in terms of per meters, per phase. The outputs of our function, if we double length:

ans =

0.007743823625000

0.096497366214921

0.000011598213856

0.096496912799382

0.000011598269400

As cen be seen, we have the same results.

To see the ground effect, we decrease height of the circuits 20 meters on original file. Outputs are:

ans =

0.007743823625000

0.096497366214921

0.000012690114502

0.096496912799382

0.000012690484431

As can be seen, there is no change in R and X values but Y increased by 10^{-6} as excepted because real conductors' interaction with imaginary conductors increased.

Now, reduce distances between bundels by half on original file. We expect that; R wil not change because it depends on line type and bundle number, which we not change. X will increase because GMR decrease (since it is in the denominator). For the same reason, capacitance will decrease but we output suceptance reactance, which will increase because of the its inverse relationship with capacitive reactance. Let's see our outputs:

ans =

0.007743823625000

0.112829261892198

0.000009891902070

0.112829233571570

0.000009891904594

It can be easily seen that our expectations are correct.

Now, double the bundels on original file. We expect to see the inverse of the previous effects except R because, now, we are increasing GMR, contrary to previous situation. R value will decrease to its half because each bundle have same resistance parallel to each other. X will decrease, Y will increase. Let's see our outputs:

ans =

0.003871911812500

0.069855065857660

0.000015929163860

0.069855064707980

0.000015929164125

Again, it can be easily seen that our expectations are correct.

To see the GMD effect, we will multiply all x-coordinates by 10 on original file. We expect inverse effect of GMR case because GMD is in the nominator of the ln() function in equations. R will not change since we did not change bundle or circuit number. X will increase, Y will decrease for the reasons we explained before:

ans =

0.007743823625000

0.103284616135512

0.000010844039090

0.103284725203113

0.000010844027410

It seems that we are never wrong. We are good to go with Phase-3.

In Part-3, we are asked to find ABCD parameters of the line. This part is simpler than the previous parts because, in previous parts, we have already found almost all the parameters that we will use to solve this part. For medium line parameters, we used nominal-pi model. Therefore, we need total series empedance(Z) and total shunt suceptance(Y) per phase. We have already found total series resistance per kilometer per phase(r), total series inductance per kilometer per phase(x) and total shunt suceptance per kilometer per phase(b) in Part-2, so, we must multiply them by the length of the line.

$$Z = (r + i * x) * length$$

$$Y = i * b * length$$

$$\gamma l = \sqrt{Z * Y}$$

$$Z_0 = \sqrt{Z/Y}$$

We know that for medium length:

$$A = D = 1 + \frac{Z * Y}{2}$$

$$B = Z\ \Omega$$

$$C = Y * \left(1 + \frac{Y * Z}{4}\right)\ \mho$$

Also, for long length:

$$A = D = \cosh(\gamma l)$$

$$B = Z_0 * \sinh(\gamma l)\ \ \Omega$$

$$C = \frac{\sinh(\gamma l)}{Z_0}\ \mho$$

We implement this formulas on MATLAB. Now, we are ready to test our results. We have already tested and showed that the previous parts works well. Therefore, it is enough to show that this parts works. We will use one of the work-outs, Exercise-2 that provided to us to study, which can be found on odtuclass under April 13- April 19 week. We will use this exercise data because it includes both medium and long length questions and the solution is avaliable.

Figure 3 shows the results that our function gives us. Angles are in terms of degrees and ABCD paremeters are in their corresponding form and in their corresponding space. For example, the absulute value of B parameter in medium line assumption is 122.3764 Ω, in first matrix (note that multiplier 100 is outside the matrix) and its angle is 78.69°, in second matrix.

```
medium_length_abs =

   1.0e+02 *

   0.009539645177133   1.223764683262268
   0.000007503136260   0.009539645177133


medium_length_angles =

   0.553528048630354  78.690067525979785
  90.270243402131342   0.553528048630354


long_length_abs =

   1.0e+02 *

   0.009543019347293   1.205056399549613
   0.000007562592119   0.009543019347293


long_length_angles =

   0.544871447074163  78.867171032239639
  90.177103506259854   0.544871447074163
```

Figure 3: Test results that our function gives for both medium and long length models.

$$A = D = 1 + \frac{YZ}{2} = 0.95392 + j9.216 \times 10^{-3} = \boxed{0.95396 \angle 0.5535^{\circ}}$$

$$B = Z = 24 + j120 = \boxed{122.376 \angle 78.69^{\circ} \ \Omega}$$

$$C = Y\left(1 + \frac{YZ}{4}\right) = -3.54 \times 10^{-6} + j7.503 \times 10^{-4} = \boxed{7.503 \times 10^{-4} \angle 90.27^{\circ} \ \mho}$$

Figure 4: Real answers for medium length model provided to us.

If we compare Figure 3 and Figure 4, we see that the only difference is due to the significant figures that are used in manual calculations in Figure 4. Now, we can check long line model:

$$A = D = \cosh\gamma l = \cosh(\alpha l)\cos(\beta l) + j\sinh(\alpha l)\sin(\beta l)$$

$$= \cosh(0.0302)\cos\left(\frac{0.3051}{\pi}\times 180\right) + j\sinh(0.0302)\sin\left(\frac{0.3051}{\pi}\times 180\right)$$

$$= 0.954252 + j\,9.073\times10^{-3} = \boxed{0.954295\ \angle 0.54475^\circ}$$

$$B = Z_0\sinh\gamma l = Z_0\left[\sinh(\alpha l)\cos(\beta l) + j\cosh(\alpha l)\sin(\beta l)\right]$$

$$= 399.179\angle{-5.655^\circ}\left[0.02881 + j\,0.3\right]$$

$$= 23.265 + j118.25$$

$$\boxed{= 120.514\ \angle 78.87^\circ\ \Omega}$$

$$C = \frac{\sinh\gamma l}{Z_0} = \frac{0.02881 + j0.3}{399.179\angle{-5.655^\circ}} = \boxed{7.55\times10^{-4}\angle 90.17^\circ\ \mho}$$

Figure 5: Real answers for long length model provided to us.

Again, if we compare Figure 3 and Figure 5, we see that the only difference is due to the significant figures that are used in manual calculations in Figure 5. Our function for Part-3 seems to work very well.

Also, note that there is not so much difference between medium and long line models. One can approximate very close using medium length model to decrease compitational compexity.

In hot weather, power lines can overheat just as people and animals do. The lines are often heavily loaded because of increased power consumption, and the conductors, which are generally made of copper or aluminum, expand when heated. That expansion increases the slack between transmission line structures, causing them to sag.

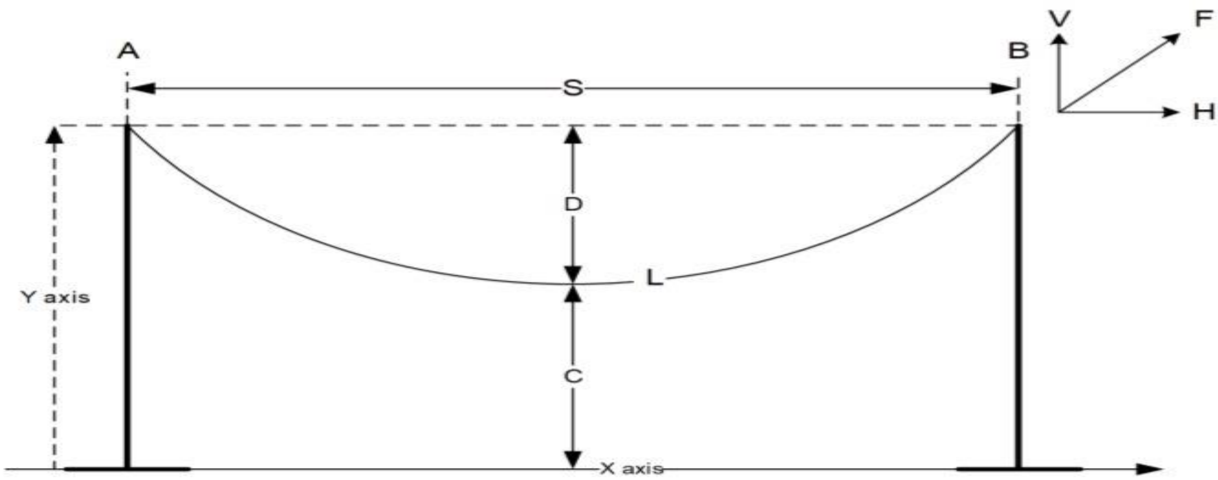

Figure 6: Sagging and related parameters.

Transmission lines are designed to meet the requirements of state electrical codes. State codes provide minimum distances between wires, poles, the ground and buildings. Industry standards are often more strict and are incorporated in transmission line design, construction and maintenance. As a precaution, no one should be on an object or in contact with an object taller than 15 to 17 feet while under a high-voltage line.

Related equations:

$$D = \frac{w * S^2}{8H} = \sqrt{\frac{3S * (L - S)}{8}}$$

$$L = S * \left(1 + \frac{S^2 * w^2}{24H^2}\right) = S + \frac{8D^2}{3S}$$

References:

Wydra, M., Kisala, P., Harasim, D., & Kacejko, P. (2018). Overhead Transmission Line Sag Estimation Using a Simple Optomechanical System with Chirped Fiber Bragg Gratings. Part 1: Preliminary Measurements. *Sensors (Basel, Switzerland)*, *18*(1), 309. https://doi.org/10.3390/s18010309

Grigsby, L. L. (2012). Electric power generation, transmission, and distribution. Boca Raton, FL: CRC Press

Grainger, J. J., & Stevenson, W. D. (1994). *Power system analysis*. New York: McGraw-Hill.