Appendix A

i) Phase-to-phase-to-earth fault loop.docx

ii) Phase-to-phase-to-earth fault loop.pdf

Appendix A

Single Phase-to-Earth Fault Loop

The theoretical equation derivation to determine the type of sequence network and the positive sequence impedance for an A-phase-to-earth fault is shown below. It is important to note that these derivations are made from a simplistic radial network with a single source of supply.

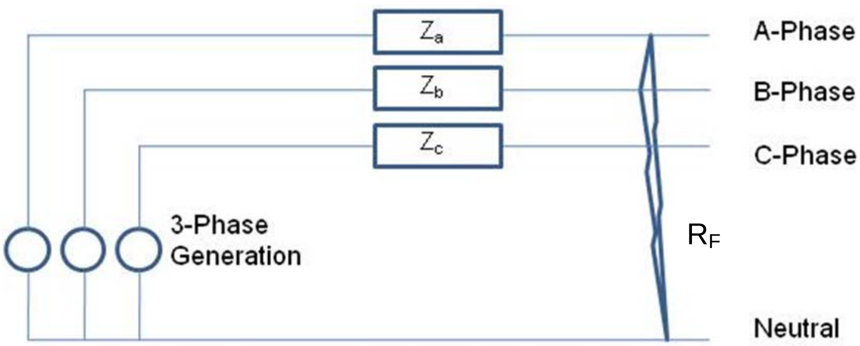


Figure 1: A-Phase-to-Earth Fault.

From figure 1 the following conclusions can be made at the point of fault for $R_F = 0$ [**Error! Reference source not found.**], [**Error! Reference source not found.**], [**Error! Reference source not found.**]

$$V_a = 0$$
$$I_b = I_c = 0$$

Writing Ib and Ic in their respective symmetrical components gives

$$I_b = \alpha^2 I_1 + \alpha I_2 + I_0$$

$$I_c = \alpha I_1 + \alpha^2 I_2 + I_0$$

Through subtraction of I_c from I_b we get

$$I_b - I_c = \left(\alpha^2 - \alpha\right)I_1 + \left(\alpha - \alpha^2\right)I_2 = 0$$

$$-\left(\alpha^2 - \alpha\right)I_1 = \left(\alpha - \alpha^2\right)I_2$$

$$I_1 = I_2$$

and by addition

$$I_b + I_c = \left(\alpha^2 + \alpha\right)I_1 + \left(\alpha + \alpha^2\right)I_2 + 2I_0$$

also

$$\left(\alpha+\alpha^{2}\right)=-1$$

Which gives

$$I_b + I_c = -I_1 + (-I_1) + 2I_0 = 0$$

$$I_1 = I_0$$

therefore

$$I_1 = I_2 = I_0$$

From this we can draw the positive-, negative- and zero sequence components in a series configuration as shown in Figure 2 below.

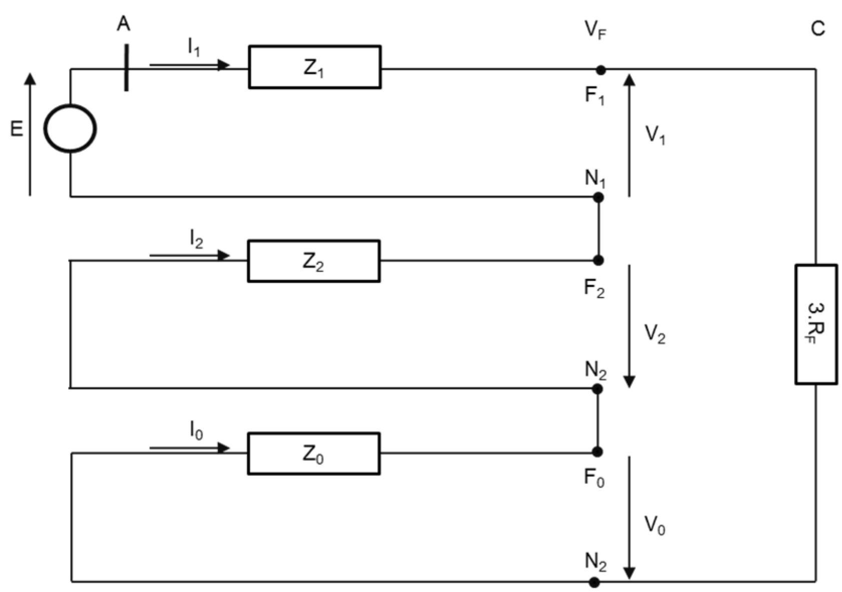


Figure 2: Symmetrical components.

If we now write the voltage Va at the point of fault in its symmetrical components we get

$$V_a = V_F = E - I_1 Z_1 - I_2 Z_2 - I_0 Z_0$$

and

$$V_a = 3I_0 R_F$$

therefore

$$3I_0R_F = E - I_1Z_1 - I_2Z_2 - I_0Z_0$$

$$E = I_1Z_1 + I_2Z_2 + I_0Z_0 + 3I_0R_F$$

add and subtract I_0Z_1

$$E = I_1Z_1 + I_2Z_2 + I_0Z_1 + I_0Z_0 - I_0Z_1 + 3I_0R_F$$

$Z_1 = Z_2$ therefore

$$E = Z_1(I_1 + I_2 + I_0) + \frac{3I_0}{3}\left(\frac{Z_0}{Z_1} - Z_1\right)Z_1 + 3I_0R_F$$

$$K_0 = \frac{1}{3}\left(\frac{Z_0}{Z_1} - 1\right)$$

therefore

$$E = Z_1(I_1 + I_2 + I_0) + 3I_0K_0Z_1 + 3I_0R_F$$

$$E = Z_1\left(I_a + 3I_0K_0\right) + 3I_0R_F$$

$$Z_1 = \frac{E - 3I_0R_F}{\left(I_a + 3I_0K_0\right)}$$

$$Z_1 = \frac{E}{\left(I_a + 3I_0K_0\right)} - \frac{3I_0R_F}{\left(I_a + 3I_0K_0\right)}$$

For a radial system $I_a = 3I_0$. Replacing I_a with $3I_0$ in the second term gives

$$Z_1 = \frac{E}{\left(I_a + 3I_0K_0\right)} - \frac{3I_0R_F}{3I_0\left(1 + K_0\right)}$$

therefore

$$Z_1 = \frac{E}{\left(I_a + 3I_0K_0\right)} - \frac{R_F}{\left(1 + K_0\right)}$$

Should the fault resistance be equal to zero, the equation simplifies to the well known equation for single phase faults.

$$Z_1 = \frac{E}{\left(I_a + 3I_0K_0\right)}$$

Appendix B

i) Phase-to-phase-to-earth fault loop.docx

ii) Phase-to-phase-to-earth fault loop.pdf

Appendix B

Phase-to-Phase-to-Earth Fault Loop

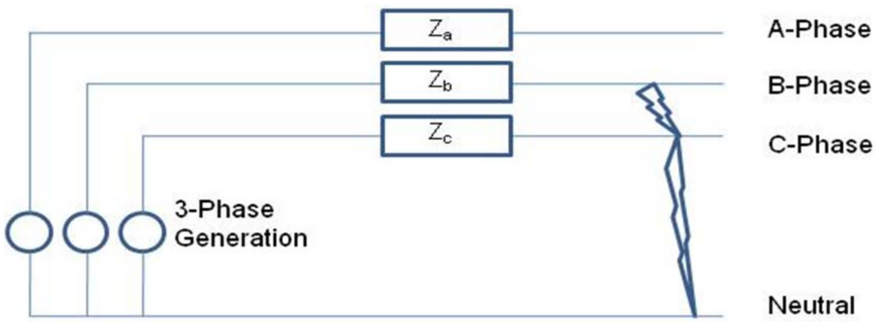


Figure 2: B to C-Phase to Earth Fault.

From figure 2 the following conclusions can be made;

At the point of fault [**Error! Reference source not found.**], [**Error! Reference source not found.**], [**Error! Reference source not found.**]

$$I_a = 0$$
$$V_b = V_c = 0$$

Writing Vb and Vc in their respective symmetrical components give

$$V_b = \alpha^2 E - \alpha^2 I_1 Z_1 - \alpha I_2 Z_2 - I_0 Z_0$$
$$V_c = \alpha E - \alpha I_1 Z_1 - \alpha^2 I_2 Z_2 - I_0 Z_0$$

Multiplying Vc by α and subtracting Vc form Vb gives

$$V_b - \alpha V_c = (1-\alpha) I_2 Z_2 - (1-\alpha) I_0 Z_0$$

therefore;

$$I_0 = \frac{I_2 Z_2}{Z_0}$$

After assigning Vb and Vc to its symmetrical components and through some mathematical manipulation it can be shown that [**Error! Reference source not found.**]

$$E = I_1\left[Z_1 + \frac{Z_2 Z_0}{Z_2 + Z_0}\right]$$

and

$$I_1 = I_1 + I_2 + I_0 = 0$$
$$I_b = \alpha^2 I_1 + \alpha I_2 + I_0 = \frac{-j\sqrt{3}E\left(Z_0 - \alpha Z_2\right)}{Z_1 Z_2 + Z_2 Z_0 + Z_0 Z_1}$$
$$I_c = \alpha I_1 + \alpha^2 I_2 + I_0 = \frac{j\sqrt{3}E\left(Z_0 - \alpha^2 Z_2\right)}{Z_1 Z_2 + Z_2 Z_0 + Z_0 Z_1}$$

Appendix C

i) Phase-to-phase fault loop.docx

ii) Phase-to-phase fault loop.pdf

Appendix C

Phase-to-Phase Fault Loop

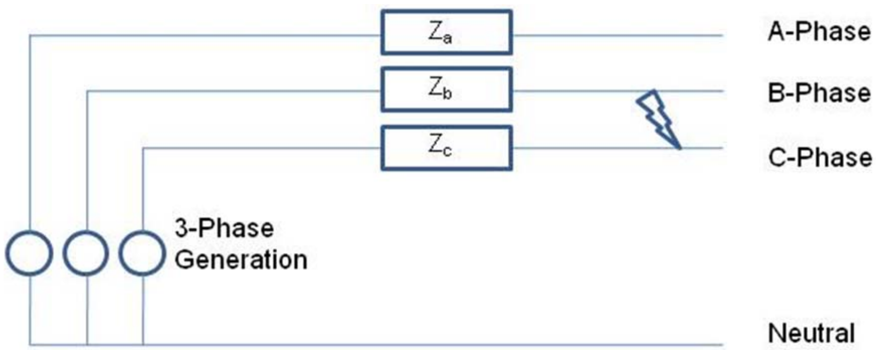


Figure 3: B-C-Phase Fault.

From figure 3 the following conclusions can be made

At the point of fault [**Error! Reference source not found.**]

$$V_a = 0$$
$$V_b = V_c = V$$

Again after assigning Vb and Vc to its symmetrical components and through some mathematical manipulation it can be shown that [**Error! Reference source not found.**]

$$E = I_1(Z_1 + Z_2)$$

and

$$I_a = I_1 + I_2 = 0$$
$$I_b = \alpha^2 I_1 + \alpha I_2 = \frac{-j\sqrt{3}E}{Z_1 + Z_2}$$
$$I_c = \alpha I_1 + \alpha^2 I_2 = \frac{j\sqrt{3}E}{Z_1 + Z_2}$$

Appendix D

i) Three-phase and three-phase-to-earth fault loop.docx

ii) Three-phase and three-phase-to-earth fault loop.pdf

Appendix D

Three Phase and Three Phase-to-Earth Fault Loop

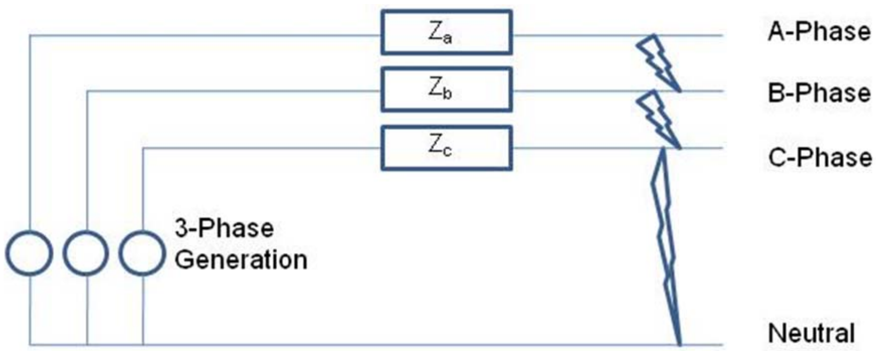


Figure 4: Three-Phase-to-Earth Fault.

From figure 4 the following conclusions can be made

At the point of fault [**Error! Reference source not found.**]

$$V_a = V_b = V_c = 0$$
$$I_a + I_b + I_c = 0$$

After assigning the currents and voltages to their relative symmetrical components and through some mathematical manipulation [**Error! Reference source not found.**] has shown that

$$I_1 = \frac{E}{Z_1}$$
$$I_2 = 0$$
$$I_0 = 0$$

and;

$$V_a = E - I_1 Z_1 - I_2 Z_2 - I_0 Z_0 = 0$$
$$V_b = \alpha^2 E - \alpha^2 I_1 Z_1 - \alpha I_2 Z_2 - I_0 Z_0 = 0$$
$$V_c = \alpha E - \alpha I_1 Z_1 - \alpha^2 I_2 Z_2 - I_0 Z_0 = 0$$

Also;

$$I_a = I_1 = \frac{E}{Z_1}$$

$$I_b = \alpha^2 I_1 = \frac{\alpha^2 E}{Z_1}$$

$$I_c = \alpha I_1 = \frac{\alpha E}{Z_1}$$

Appendix E

i) Line impedance measurements.docx

ii) Line impedance measurements.pdf

Appendix E

Line Impedance Measurement Results

These measurements were done in conjunction with and were obtained from [**Error! Reference source not found.**].

Measurements:	**R [Ω]**	**X [Ω]**	**Z [Ω]**	**Phi (°)**
A-B: $Z_A + Z_B$	1.269	15.328	15.380	85.27°
B-C: $Z_B + Z_C$	1.128	13.808	13.853	85.33°
C-A: $Z_C + Z_A$	1.127	13.631	13.677	85.28°
A-E: $Z_A + Z_E$	1.952	9.960	10.149	78.91°
B-E: $Z_B + Z_E$	1.937	10.187	10.370	79.24°
C-E: $Z_C + Z_E$	1.913	10.235	10.412	79.41°
A-B-C-E: $Z_A//Z_B//Z_C + Z_E$	1.541	5.356	5.573	73.95°
Calculation of impedances:				
Z_A	0.634	7.576	7.602	85.22°
Z_B	0.635	7.752	7.778	85.32°
Z_C	0.493	6.055	6.075	85.35°
Z_E from Measurement A-E	1.318	2.384	2.724	61.07°
Z_E from Measurement B-E	1.302	2.435	2.761	61.87°
Z_E from Measurement C-E	1.420	4.180	4.414	71.23°
Impedance results:				
Line impedance Z_L	0.587	7.128	7.152	85.29°
Earth impedance Z_E	1.345	2.980	3.269	65.70°
Zero sequence impedance Z_0	4.623	16.067	16.718	73.95°
Earthing Factor:				
$k_L = Z_E / Z_L$			0.457	-19.591
R_E / R_L and X_E / X_L			2.291	0.418
Z_0 / Z_1			2.338	-11.344

PowerFactory / DigSilent: Simulated Line Data:

Z1: Section 1: T1 - T20	0.181	2.286		
Z1: Section 2: T21 - T61	0.373	4.481		
	0.554	6.767	6.790	85.32°

abs Error - Z1	-0.033	-0.361	-0.362
% Error - Z1	-5.65%	-5.06%	-5.06%

Z0: Section 1: T1 - T20	1.713	5.383		
Z0: Section 2: T21 - T61	2.493	10.452		
	4.206	15.835	16.384	75.12°

abs Error - Z0	-0.417	-0.232	-0.334
% Error - Z0	-9.03%	-1.44%	-2.00%

Appendix F

i) 19 Strand steel earth-wire conductor GMR.pdf

Appendix G

i) GMR and inductance of a single Dinosaur conductor.pdf

Appendix G

GMR for Stranded Earth Wire Conductor taking Metal Resitivity into account.

All calculations are done in meters.

Number of strands in the Steel-core.

$n_s := 19$

Steel Strand Diameter

$d_{ss} := 2.65 \cdot 10^{-3}$

$r_s := \frac{d_{ss}}{2}$

Number of strands in first steel layer

$n_{s1} := 6$

Number of strands in second steel layer

$n_{s2} := 12$

Permeability of steel

$\mu_s := 875 \cdot 10^{-6} \cdot H \cdot m^{-1}$

Permeability of air

$\mu_0 := 4\pi \cdot 10^{-7} H \cdot m^{-1}$

Relative Permeability of steel

$\mu_{r\_s} := \frac{\mu_s}{\mu_0}$

$\mu_{r\_s} = 696.3029$

GMR of single steel strand D_{ss}.

$$D_{ss} := r_s \cdot e^{-\frac{\mu_{r\_s}}{4}}$$

$$D_{ss} = 332.7297856981603 \times 10^{-81}$$

Number assignment to first strand in first steel layer

$$is := 2$$

Number series for other strands in first steel layer

$$jjs := is + 1 .. n_{s1} + 1$$

Angle between centre strand and two successive strands within first steel layer.

$$\alpha_{s1} := \frac{2\pi}{n_{s1} \cdot deg}$$

$$\alpha_{s1} = 60$$

Distance calculations between 1 strand in first steel layer and other strands in same layer

$$d_{sl_{2,3}} := \sqrt{(2r_s)^2 + (2r_s)^2 - 2\cdot(2r_s)\cdot(2r_s)\cdot\cos(\alpha_{s1}\cdot deg)}$$

$$d_{sl_{2,3}} = 2.65 \times 10^{-3}$$

$$d_{sl_{2,4}} := \sqrt{(2r_s)^2 + (2r_s)^2 - 2\cdot(2r_s)\cdot(2r_s)\cdot\cos(2\alpha_{s1}\cdot deg)}$$

$$d_{sl_{2,4}} = 4.589934640057525 \times 10^{-3}$$

$$d_{sl_{2,5}} := \sqrt{(2r_s)^2 + (2r_s)^2 - 2\cdot(2r_s)\cdot(2r_s)\cdot\cos(3\alpha_{s1}\cdot deg)}$$

$$d_{sl_{2,5}} = 5.3 \times 10^{-3}$$

$$d_{sl_{2,6}} := \sqrt{(2r_s)^2 + (2r_s)^2 - 2\cdot(2r_s)\cdot(2r_s)\cdot\cos(4\alpha_{s1}\cdot deg)}$$

$$d_{sl_{2,6}} = 4.589934640057526 \times 10^{-3}$$

$$d_{sl_{2,7}} := \sqrt{(2r_s)^2 + (2r_s)^2 - 2\cdot(2r_s)\cdot(2r_s)\cdot\cos(5\alpha_{s1}\cdot deg)}$$

$$d_{sl_{2,7}} = 2.6500000000000017 \times 10^{-3}$$

Product of distances in first steel layer (j).

Method 1

$$d_{SL1} := \left(\prod_{jjs} d_{sl_{is,jjs}}\right)^{\left(\frac{n_{s1}}{n_s}\right)}$$

$$d_{SL1} = 150.37402601294065 \times 10^{-6}$$

Method 2

$$d_{sl\_L1} := \left[\prod_{k=1}^{(n_{s1}-1)} \sqrt{(2r_s)^2 + (2r_s)^2 - 2\cdot(2r_s)\cdot(2r_s)\cdot\cos(k\,\alpha_{s1}\cdot deg)}\right]^{\left(\frac{n_{s1}}{n_s}\right)}$$

$$d_{sl\_L1} = 150.37402601294065 \times 10^{-6}$$

Number assignment to first strand in second steel layer

$is2 := 8$

Number series for other strands in second steel layer

$jjs := is2 + 1 .. n_s$

Angle between centre strand and two successive strands within second steel layer.

$$\alpha_{s2} := \frac{2\pi}{n_{s2} \cdot deg}$$

$$\alpha_{s2} = 29.999999999999996 \times 10^{0}$$

Distance calculations between 1 strand in layer 2 and other strands in same layer

$$d_{sl_{8,9}} := \sqrt{\left(4r_s\right)^2 + \left(4r_s\right)^2 - 2 \cdot \left(4r_s\right) \cdot \left(4r_s\right) \cdot \cos\left(\alpha_{s2} \cdot deg\right)}$$

$$d_{sl_{8,9}} = 2.7435 \times 10^{-3}$$

$$d_{sl_{8,10}} := \sqrt{\left(4r_s\right)^2 + \left(4r_s\right)^2 - 2 \cdot \left(4r_s\right) \cdot \left(4r_s\right) \cdot \cos\left(2\alpha_{s2} \cdot deg\right)}$$

$$d_{sl_{8,10}} = 5.299999999999999 \times 10^{-3}$$

$$d_{sl_{8,11}} := \sqrt{\left(4r_s\right)^2 + \left(4r_s\right)^2 - 2 \cdot \left(4r_s\right) \cdot \left(4r_s\right) \cdot \cos\left(3\alpha_{s2} \cdot deg\right)}$$

$$d_{sl_{8,11}} = 7.495331880577402 \times 10^{-3}$$

$$d_{sl_{8,12}} := \sqrt{\left(4r_s\right)^2 + \left(4r_s\right)^2 - 2 \cdot \left(4r_s\right) \cdot \left(4r_s\right) \cdot \cos\left(4\alpha_{s2} \cdot deg\right)}$$

$$d_{sl_{8,12}} = 9.17986928011505 \times 10^{-3}$$

$$d_{sl_{8,13}} := \sqrt{\left(4r_s\right)^2 + \left(4r_s\right)^2 - 2 \cdot \left(4r_s\right) \cdot \left(4r_s\right) \cdot \cos\left(5\alpha_{s2} \cdot deg\right)}$$

$$d_{sl_{8,13}} = 10.238813758664124 \times 10^{-3}$$

$$d_{sl_{8,14}} := \sqrt{\left(4r_s\right)^2 + \left(4r_s\right)^2 - 2 \cdot \left(4r_s\right) \cdot \left(4r_s\right) \cdot \cos\left(6\alpha_{s2} \cdot deg\right)}$$

$$d_{sl_{8,14}} = 10.6 \times 10^{-3}$$

$$d_{sl_{8,15}} := \sqrt{(4r_s)^2 + (4r_s)^2 - 2\cdot(4r_s)\cdot(4r_s)\cdot\cos(7\alpha_{s2}\cdot deg)}$$

$$d_{sl_{8,15}} = 10.238813758664126 \times 10^{-3}$$

$$d_{sl_{8,16}} := \sqrt{(4r_s)^2 + (4r_s)^2 - 2\cdot(4r_s)\cdot(4r_s)\cdot\cos(8\alpha_{s2}\cdot deg)}$$

$$d_{sl_{8,16}} = 9.179869280115051 \times 10^{-3}$$

$$d_{sl_{8,17}} := \sqrt{(4r_s)^2 + (4r_s)^2 - 2\cdot(4r_s)\cdot(4r_s)\cdot\cos(9\alpha_{s2}\cdot deg)}$$

$$d_{sl_{8,17}} = 7.495331880577408 \times 10^{-3}$$

$$d_{sl_{8,18}} := \sqrt{(4r_s)^2 + (4r_s)^2 - 2\cdot(4r_s)\cdot(4r_s)\cdot\cos(10\alpha_{s2}\cdot deg)}$$

$$d_{sl_{8,18}} = 5.300000000000003 \times 10^{-3}$$

$$d_{sl_{8,19}} := \sqrt{(4r_s)^2 + (4r_s)^2 - 2\cdot(4r_s)\cdot(4r_s)\cdot\cos(11\alpha_{s2}\cdot deg)}$$

$$d_{sl_{8,19}} = 2.743481878086728 \times 10^{-3}$$

Product of distances in second steel layer (j).

Method 1

$$d_{SL2} := \left(\prod_{jjs} d_{sl_{is2,jjs}}\right)^{\left(\frac{n_{s2}}{n_s}\right)}$$

$$d_{SL2} = 743.5226394242576 \times 10^{-18}$$

Method 2

$$d_{sl\_L2} := \left[\prod_{k=1}^{(n_{s2}-1)} \sqrt{(4r_s)^2 + (4r_s)^2 - 2\cdot(4r_s)\cdot(4r_s)\cdot\cos(k\,\alpha_{s2}\cdot deg)}\right]^{\left(\frac{n_{s2}}{n_s}\right)}$$

$$d_{sl\_L2} = 743.5226394242576 \times 10^{-18}$$

Product of Distances between first and Second Steel layers

$$d_{SL1\_2} := \left[\prod_{k=1}^{n_{s2}} \sqrt{(2r_s)^2 + (4r_s)^2 - 2\cdot(2r_s)\cdot(4r_s)\cdot\cos(k\,\alpha_{s2}\cdot deg)}\right]^{\frac{n_{s1}}{n_s}}$$

$$d_{SL1\_2} = 2.377769808946266 \times 10^{-9}$$

Product of Distances between Second and First Steel layers

$$d_{SL2\_1} := \left[\prod_{k=1}^{n_{s1}} \sqrt{(2r_s)^2 + (4r_s)^2 - 2\cdot(2r_s)\cdot(4r_s)\cdot\cos(k\,\alpha_{s1}\cdot deg)}\right]^{\frac{n_{s2}}{n_s}}$$

$$d_{SL2\_1} = 2.354418484718064 \times 10^{-9}$$

Product of distances between First Steel Layer and Centre strand

$$d_{SL1\_C} := (2r_s)^{\left(\frac{n_{s1}}{n_s}\right)}$$

$$d_{SL1\_C} = 153.5635596771246 \times 10^{-3}$$

Product of distances between Second Steel Layer and Centre strand

$$d_{SL2\_C} := \left(4r_s\right)^{\left(\frac{n_{s2}}{n_s}\right)}$$

$$d_{SL2\_C} = 36.534279690638954 \times 10^{-3}$$

Product of distances between centre strand and first layer

$$d_{SC\_1} := \left(2r_s\right)^{\left(\frac{n_{s1}}{n_s}\right)}$$

$$d_{SC\_1} = 153.5635596771246 \times 10^{-3}$$

Product of distances between centre strand and second layer

$$d_{SC\_2} := \left(4r_s\right)^{\left(\frac{n_{s2}}{n_s}\right)}$$

$$d_{SC\_2} = 36.534279690638954 \times 10^{-3}$$

GMR of 19 Strand Steel Earth Wire

$$GMR_{ss} := \sqrt[n_s]{D_{ss} \cdot d_{SL1} \cdot d_{SL2} \cdot d_{SL1\_2} \cdot d_{SL2\_1} \cdot d_{SL1\_C} \cdot d_{SL2\_C} \cdot d_{SC\_1} \cdot d_{SC\_2}}$$

$$GMR_{ss} = 533.566957 \times 10^{-9} \quad m$$

Appendix H

MathCAD example programs for conductor impedance

i) EMTP conductor calc.xmcd

ii) GMR StrandedAluminiumCond.xmcd

REL531 relay test folder inclusive of the following folders with test results

i) A-phase-to-earth faults

ii) Clasic test method

iii) Phase-to-phase faults

REL531 Impedance plots and calculation EXCEL file

i) REL531 Impedance plots and calculation.xls

REL531 folder with sub-folders containing test injection results.

i) A-phase-to-earth faults

ii) Classic test method

iii) Phase-to-phase faults

Appendix I

7SA513 impedance characteristics and associated calculations are found in this appendix. File 7SA513-REL comparisson.xlsx shows the relevant relay characteristics for different fault and load conditions. Original test result files for the characteristic plots done in the above file can be found in this appendix under directory 7SA513, sub-directories:

i) Classic method (no series cap bank – radial feed),
ii) Classic method (series cap bank – radial feed),
iii) Export load (no cap bank – radial feed),
iv) Export load (series cap bank – radial feed),
v) Export load (no cap bank – dual feed),
vi) Import load (no cap bank – dual feed),
vii) Import load (series cap bank incl.),
viii) Result calculations,
ix) With series cap bank (radial feed).

Appendix J

Simulation study results performed in PowerFactory software and Matlab routines written for this purpose are located here in the following files respectively;

i) Phase-to-earth PowerFactory simulation results.xlsx

ii) MatlabStudyResults.docx

Appendix K

Matlab routine m and asv-files are located here.

i) FaultPosNew.asv

ii) FaultPosNew.m

iii) ImpCalcNew.asv

iv) ImpCalcNew.m

v) PlotGraph.asv

vi) PlotGraph.m

vii) VariablesNew.asv

viii) VariablesNew.m

Appendix L

i) Magnetic permeability.docx

ii) Magnetic permeability.pdf

Appendix L

Magnetic permeability & susceptibility for selected materials			
Medium	**Susceptibility**	**Initial Permeability**	
Mumetal	20,000 [1]	25,000 μN/A^2	at 0.002 T
Permalloy	8000 [1]	10,000 μN/A^2	at 0.002 T
Transformer iron	4000 [1]	5000 μN/A^2	at 0.002 T
Steel	700 [1]	875 μN/A^2	at 0.002 T
Nickel	100 [1]	125 μN/A^2	at 0.002 T
Platinum	2.65×10^{-4}	1.2569701 μN/A^2	
Aluminum	2.22×10^{-5} [2]	1.2566650 μN/A^2	
Hydrogen	8×10^{-9} or 2.2×10^{-9} [2]	1.2566371 μN/A^2	
Vacuum	0	1.2566371 μN/A^2	
Sapphire	-2.1×10^{-7}	1.2566368 μN/A^2	
Copper	-6.4×10^{-6} or -9.2×10^{-6} [2]	1.2566290 μN/A^2	
Water	-8.0×10^{-6}	1.2566270 μN/A^2	

Permeability varies with flux density. Values shown are approximate and valid only at the flux densities shown.

[edit]
References

1. ^ a b c d e "Relative Permeability", *Hyperphysics*
2. ^ a b c Clarke, R. *Magnetic properties of materials*, surrey.ac.uk

Appendix M

i) Siemens performance guarantee.docx

Appendix M

Siemens Performance Guarantee for 7SA513 V2.2 - PG1

Operating Time

a) The operating time of the 7SA513 protection relay is specified in tables 1...3 for the 1st zone (Z1).

b) The fault detection for faults outside the 1st zone has the following operating times provided the fault currents and voltages exceed the set values, in particular for ground faults the residual current and/or residual voltage:
max. 30ms for non compensated lines >5Ω secondary
max. 40ms for lines <5Ω secondary and series compensated lines

c) Time delays for all the zones are started by the fault detection signal and therefore the total tripping depends on b).

The influence of the CVT on the operating time of the 7SA513 protection relay as shown in the tables 1..3 depends on the characteristic of the CVT. The specified CVT influence was observed using a CVT model with secondary burden of 40 Ω at 57 V. By reducing the 40 Ω resistance, the damping will increase and the CVT influence on the tripping times will reduce.

Phase Selection

The 7SA513 protection relay will trip with correct phase selection for all faults on the protected line. This correct phase selection is guaranteed for all faults with actual fault resistance up to 10 Ω secondary and the fault detection polygon is set as shown in the enclosed Siemens recommendation.
For loads > 0.5 × I_N it is possible to have additional loop flagging, which has no influence on the correct tripping.

Directional Determination

The 7SA513 protection relay will always provide correct directional determination under the following circumstances:
Overall transmission angle of the system (generator angles) γ ≤ 60° elec. and the relay setting along the R-axis ≤ 20 Ω secondary
With smaller transmission angles, larger R-axis settings can be tolerated.

The non-directional decision has the same significance and reaction as the reverse decision. A non-directional decision cannot occur for a forward fault.

Reach

The steady state reach measuring accuracy of the 7SA513 relay is ± 5% of reach setting. Transient overreach adds no more than 10% in the case of non-series compensated lines. The presence of series compensation adds a further 5% to the measuring error. If set as follows no underreach or overreach occurs:

	Reach Setting Limitation			
	Non-Series Compensated Lines		Series Compensated Lines	
	Single Line	Parallel Line	Single Line	Parallel Line
3 Pole Tripping	$X1 = 85\% X_L$ $X1b = 125\% X_L$	$X1 = 85\% X_L$ $X1b = 150\% X_L$	$X1 = 80\% (X_L - X_C)$ $X1b = 125\% X_L$	$X1 = 80\% (X_L - X_C)$ $X1b = 150\% X_L$
1+3 Pole Tripping	$X1 = 80\% X_L$ $X1b = 125\% X_L$	$X1 = 80\% X_L$ $X1b = 150\% X_L$	$X1 = 75\% (X_L - X_C)$ $X1b = 130\% X_L$	$X1 = 75\% (X_L - X_C)$ $X1b = 150\% X_L$

with X_L = line reactance, X_C = series capacitor, X1 = zone 1 setting, X1b = overreach zone setting, Parrallel Line = both lines in service

Fault resistance is assumed to only appear between phase and earth. The effect of fault resistance under load flow conditions on the reach of the 7SA513 protection relay during single phase to ground faults is compensated for under the following conditions:

a) The fault resistance is less than 10 Ω secondary.
b) The earth fault current is greater than 20% of the nominal current I_N.

In the case of phase to phase to earth faults, the block leading phase setting must be selected to avoid an unwanted overreach.
For fault resistances that are greater than 10 Ω secondary, the attached curves indicate the influence on the reach accuracy.
Compensation for reach changes that may occur with sequential faults during the single pole dead time is not available. With load currents greater than 0.5 × I_N and settings according to the above table phase-phase-faults during the single pole dead time may lead to overreach or underreach on long lines.

The influence of the coupling effect of a parallel line on the reach accuracy of the 7SA513 relay can be compensated by using the corresponding feature in the 7SA513 relay.

Timing of Alarm Output Contact

Timing difference between alarm and trip signals are due to two effects. Firstly the command (trip) relays have a faster operating time than the alarm relays. Maximum difference is 6 ms. Secondly, certain alarms are treated as fast alarms and are available at the same speed as a trip signal while other alarms are treated as slow alarms and are subject to an additional delay.

	Trip Contact (Command Relay)	Alarm Contact (Alarm Relay)
Trip Command	0 ms	+ 4 ms
Fast alarm (eg No. 510)	1 - 6 ms	5 - 10 ms
Slow alarm (eg No. 151)	10 - 30 ms	14 - 34 ms

Enclosures

1. Table 1, Table 2, Table 3
2. Siemens recommendation for setting the relay fault detection characteristic
3. Effect of fault resistance on relay reach

		Typical Operating Times (ms)							
		> 5 Ω secondary				≤ 5 Ω secondary			
		Fault Location: 0-20% of Z1-reach	Fault Location: 20-60% of Z1 reach	Fault Location: 60-90% of Z1 reach	Sequential ** Fault during single pole dead time and evolving fault	Fault Location: 0-20% of Z1 reach	Fault Location: 20-60% of Z1 reach	Fault Location: 60-90% of Z1 reach	Sequential Fault during single pole dead time and evolving fault
SIR < 20	Export High Load $I > 0.5 \times I_N$	18	20	25	30	18	20	25	30
	Import High Load $I > 0.5 \times I_N$	20	20	30	45	18	20	30	45
	Low Load $I \leq 0.5 \times I_N$	18	20	25	30	18	20	25	30
20 < SIR < 30	Export High Load $I > 0.5 \times I_N$	18	20	25	30	20	25	25	30
	Import High Load $I > 0.5 \times I_N$	20	20	30	45	20	25	30	45
	Low Load $I \leq 0.5 \times I_N$	18	20	25	30	20	20	25	30
Influence of CVT's only on ph-ph and ph-ph-g faults		-	-	-	-	+ 10	+ 10	+ 10	+10
Influence of series compensation *		+ 5	+ 5	+ 5	+5				
Influence of fault resistance ≤10 Ω sec.		-	-	-	-	-	-	-	-

Table 1

* Gap flashover (if it occurs) is assumed to take place not later than 5ms after fault inception.

** For sequential faults occuring more than 250ms after the 1st fault inception the tripping time will be as stated for the 1st fault condition

		Maximum Operating Times (ms)							
		> 5 Ω secondary				≤ 5 Ω secondary			
		Fault Location: 0-20% of Z1 reach	Fault Location: 20-60% of Z1 reach	Fault Location: 60-90% of Z1 reach	Sequential ** Fault during single pole dead time and evolving fault	Fault Location: 0-20% of Z1 reach	Fault Location: 20-60% of Z1 reach	Fault Location: 60-90% of Z1 reach	Sequential Fault during single pole dead time and evolving fault
SIR < 20	Export High Load $I > 0.5 \times I_N$	22	25	30	30	22	25	30	30
	Import High Load $I > 0.5 \times I_N$	22	25	35	45	22	25	35	45
	Low Load $I \leq 0.5 \times I_N$	22	22	30	30	22	25	30	30
20 < SIR < 30	Export High Load $I > 0.5 \times I_N$	22	25	30	30	30	30	30	30
	Import High Load $I > 0.5 \times I_N$	22	25	35	45	30	30	35	45
	Low Load $I \leq 0.5 \times I_N$	22	22	30	30	30	30	30	30
Influence of CVT's only on ph-ph and ph-ph-g faults		-	-	-	-	+ 20	+ 20	+ 20	+20
Influence of series compensation *		+ 10	+ 10	+ 10	+10				
Influence of fault resistance ≤10Ωsec.		-	-	-	-	-	-	-	-

Table 2

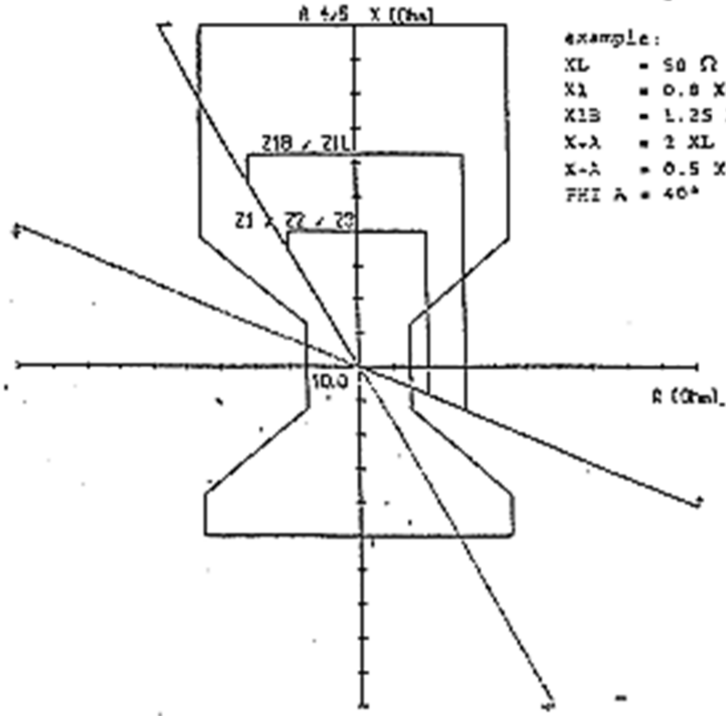
* Gap flashover (if it occurs) is assumed to take place not later than 5ms after fault inception. For delayed or asymmetrical flashover a further delay of 20ms (occacionally 28ms) can be expected.

** For sequential faults occuring more than 250ms after the 1st fault inception the tripping time will be as stated for the 1st fault condition

	Line Check Trip - Operating Time (ms)	
	Typical	Maximum
Fault Current ≥ S.O.T.F. Setting (2404) Isc	12	15
Fault Current < S.O.T.F. Setting (2404) Isc and Fault Location in Overreach Zone Z1b	25	30

Table 3

Recommendation for setting of fault detection (ZA), zone 1 (Z1), overreach zone (Z1B), (1) of (2)

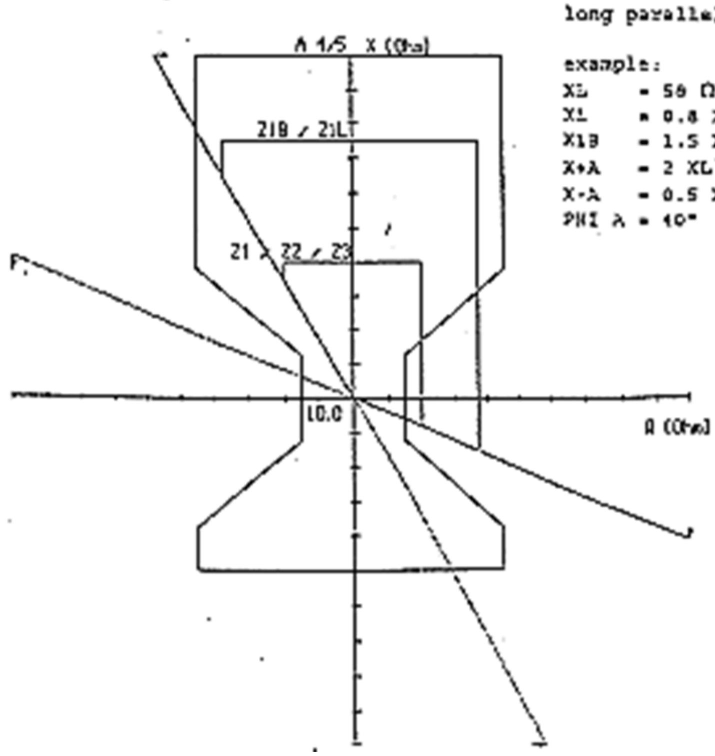


long single line

example:

XL = 50 Ω sek.
X1 = 0.8 XL
X1B = 1.25 XL
X+A = 2 XL
X-A = 0.5 X+A
PHI A = 40°

R1 = R1E = 0.5 X1
R1B = R1BE = 0.5 X1B
RA1 = RA1E = 15 Ω sek.
RA2 = RA2E = 45 Ω sek.
PHI AE = 40°



long parallel line

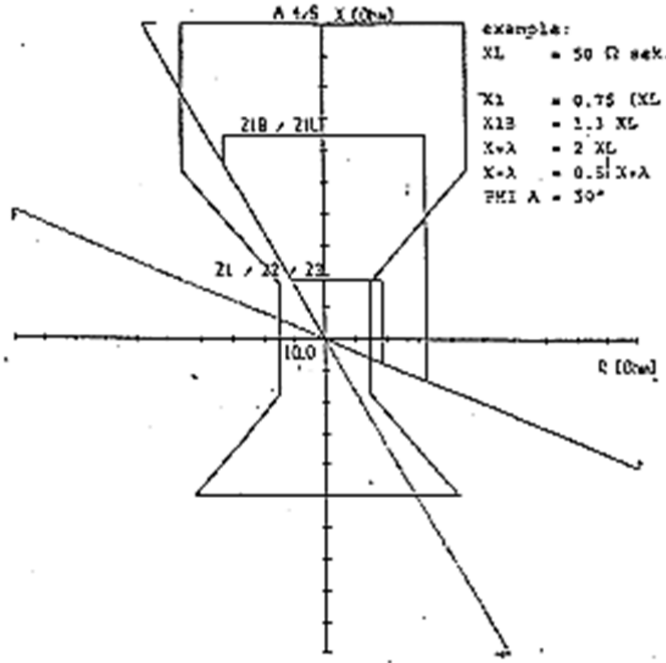
example:

XL = 50 Ω sek.
X1 = 0.8 XL
X1B = 1.5 XL
X+A = 2 XL
X-A = 0.5 X+A
PHI A = 40°

R1 = R1E = 0.5 X1
R1B = R1BE = 0.5 X1B
RA1 = RA1E = 15 Ω sek.
RA2 = RA2E = 45 Ω sek.
PHI AE = 40°

Recommendation for setting of fault detection (ZA), zone 1 (Z1), overreach zone (Z1B), (2) of (2)

series compensated single line



example:

XL = 50 Ω sek. XC = 25 Ω sek.

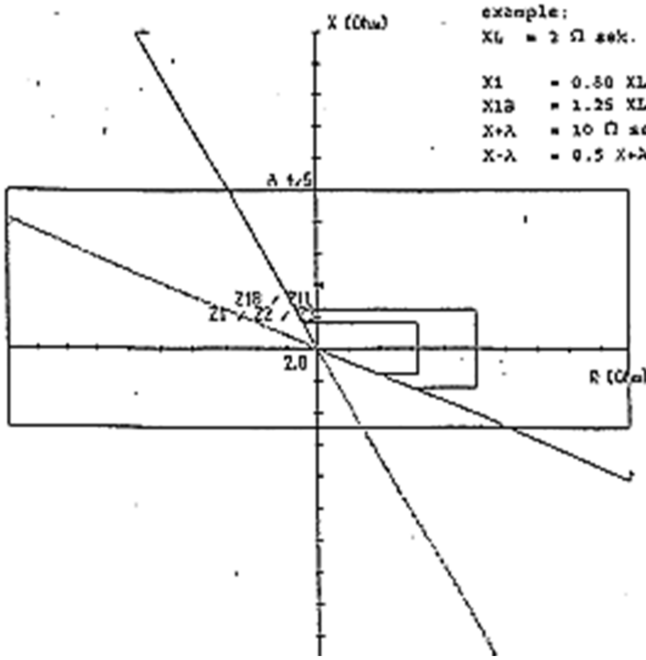
X1	= 0.75 (XL - XC)	R1 = R1E	= 0.5 * 0.75 XL
X1B	= 1.3 XL	R1B = R1BE	= 0.5 X1B
X+λ	= 2 XL	RA1 = RA1E	= 15 Ω sek.
X-λ	= 0.5 X+λ	RA2 = RA2E	= 45 Ω sek.
PHI λ	= 30°	PHI λE	= 50°

short line

example:

XL = 2 Ω sek.

X1	= 0.80 XL	R1 = R1E	= 4 X1
X1B	= 1.25 XL	R1B = R1BE	= 4 X1B
X+λ	= 10 Ω sek.	RA1 = RA1E	= 20 Ω sek.
X-λ	= 0.5 X+λ	RA2 = RA2E	= 10 Ω sek.



Effect of load and fault resistance on distance relay reach, (1) of (2)

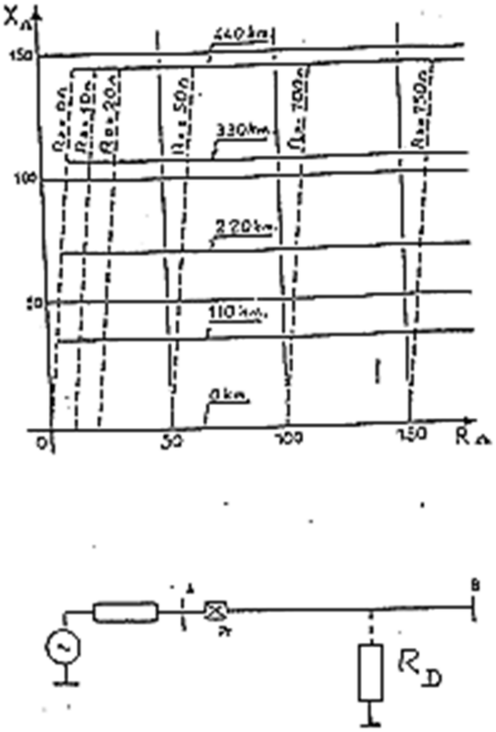


Fig. 1: Unloaded Line, open at one end

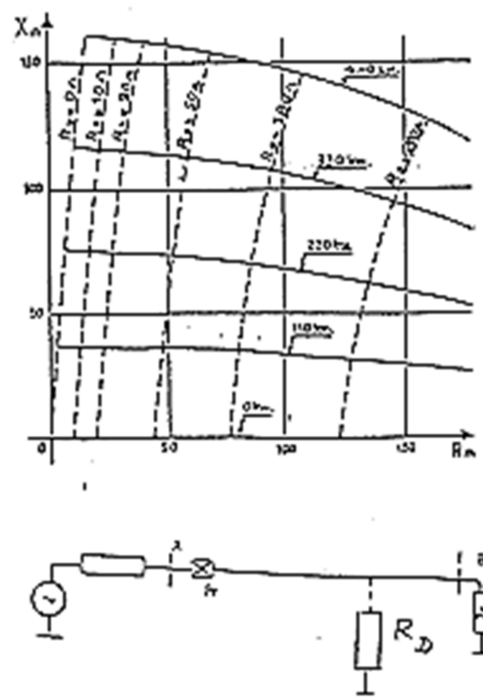


Fig. 2: Unloaded Line, terminated with characteristic impedance

Appendix N

i) Table of resistivity.docx

Appendix N

Table of Resistivity

Material	Resistivity (Ω·m) at 20 °C	Temperature coefficient* [K^{-1}]	Reference
Silver	1.59×10^{-8}	0.0038	[1][2]
Copper	1.72×10^{-8}	0.0039	[2]
Gold	2.44×10^{-8}	0.0034	[1]
Aluminium	2.82×10^{-8}	0.0039	[1]
Tungsten	5.60×10^{-8}	0.0045	[1]
Iron	1.0×10^{-7}	0.005	[1]
Tin	1.09×10^{-7}	0.0045	
Platinum	1.06×10^{-7}	0.00392	[1]
Lead	2.2×10^{-7}	0.0039	[1]
Manganin	4.82×10^{-7}	0.000002	[3]
Constantan	4.9×10^{-7}	0.000 008	[4]

Mercury	9.8×10^{-7}	0.0009	[3]
Nichrome[5]	1.10×10^{-6}	0.0004	[1]
Carbon[6]	3.5×10^{-5}	−0.0005	[1]
Germanium[6]	4.6×10^{-1}	−0.048	[1][2]
Silicon[6]	6.40×10^{2}	−0.075	[1]
Glass	10^{10} to 10^{14}		[1][2]
Hard rubber	approx. 10^{13}		[1]
Sulphur	10^{15}		[1]
Quartz (fused)	7.5×10^{17}		[1]

1. Serway, Raymond A. (1998). *Principles of Physics* (2nd edition). Fort Worth, Texas, London: Saunders College Pub. pp. 602. ISBN 0-03-020457-7.
2. Griffiths, David (1999) [1981]. "7. Electrodynamics". in Alison Reeves (ed.). *Introduction to Electrodynamics* (3rd edition ed.). Upper Saddle River, New Jersey: Prentice Hall. pp. 286. ISBN 0-13-805326-x. OCLC 40251748.
3. Giancoli, Douglas C. (1995). *Physics: Principles with Applications* (4th edition.). London: Prentice Hall. ISBN 0-13-102153-2.
   (see also Table of Resistivity)
4. John O'Malley, *Schaum's outline of theory and problems of basic circuit analysis*, p.19, McGraw-Hill Professional, 1992 ISBN 0070478244

Appendix O

i) Temperature coefficients of resistance.docx

ii) Temperature coefficients of resistance.docx

Appendix O

Temperature Coefficients of Resistance, at 20°C

Material	Element/Alloy	α per °C
Nickel	Element	0.005866
Iron	Element	0.005671
Molybdenum	Element	0.004579
Tungsten	Element	0.004403
Aluminium	Element	0.004308
Copper	Element	0.004041
Silver	Element	0.003819
Platinum	Element	0.003729
Gold	Element	0.003715
Zinc	Element	0.003847
Steel *	Alloy	0.003
Nichrome	Alloy	0.00017
Nichrome V	Alloy	0.00013
Manganin	Alloy	+/- 0.000015
Constantan	Alloy	0.000074

* = Steel alloy at 99.5 percent iron, 0.5 percent carbon

Lessons In Electric Circuits, Volume I – DC
By Tony R. Kuphaldt
Fifth Edition, last update October 18, 2006

Appendix P

The following results files can be found in this appendix:

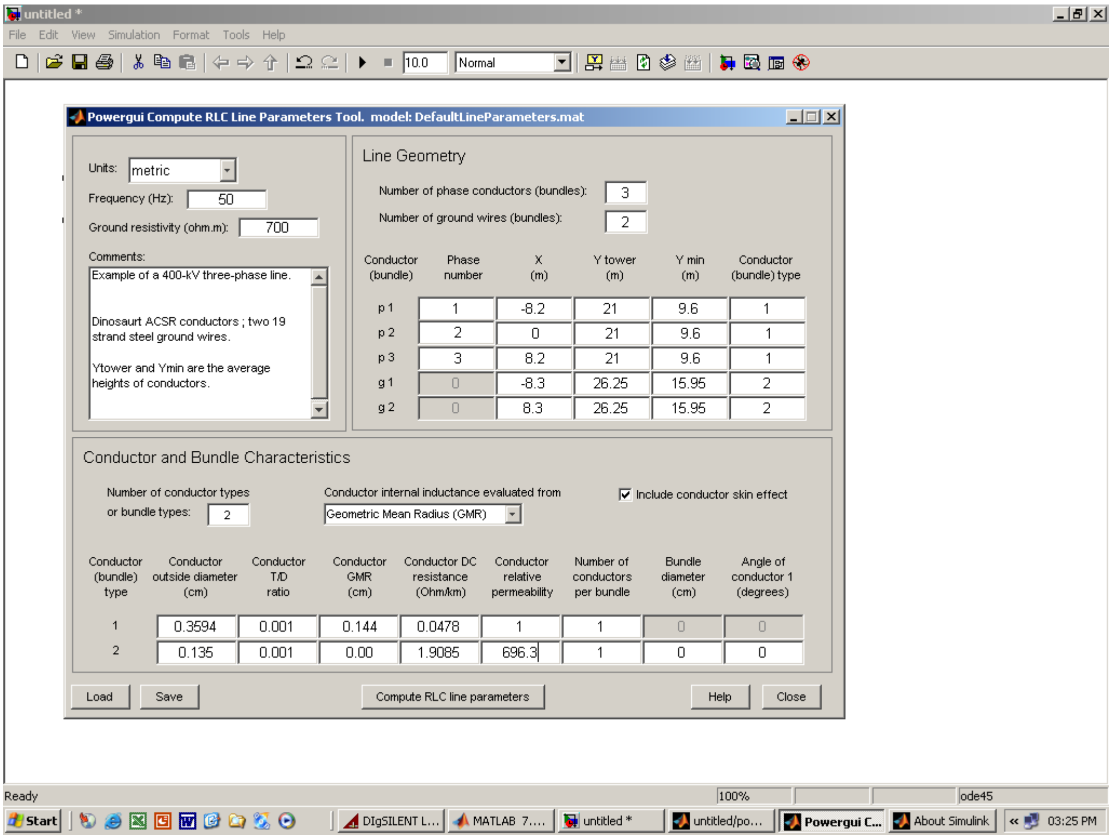
i) MatlabLineParameters.pdf

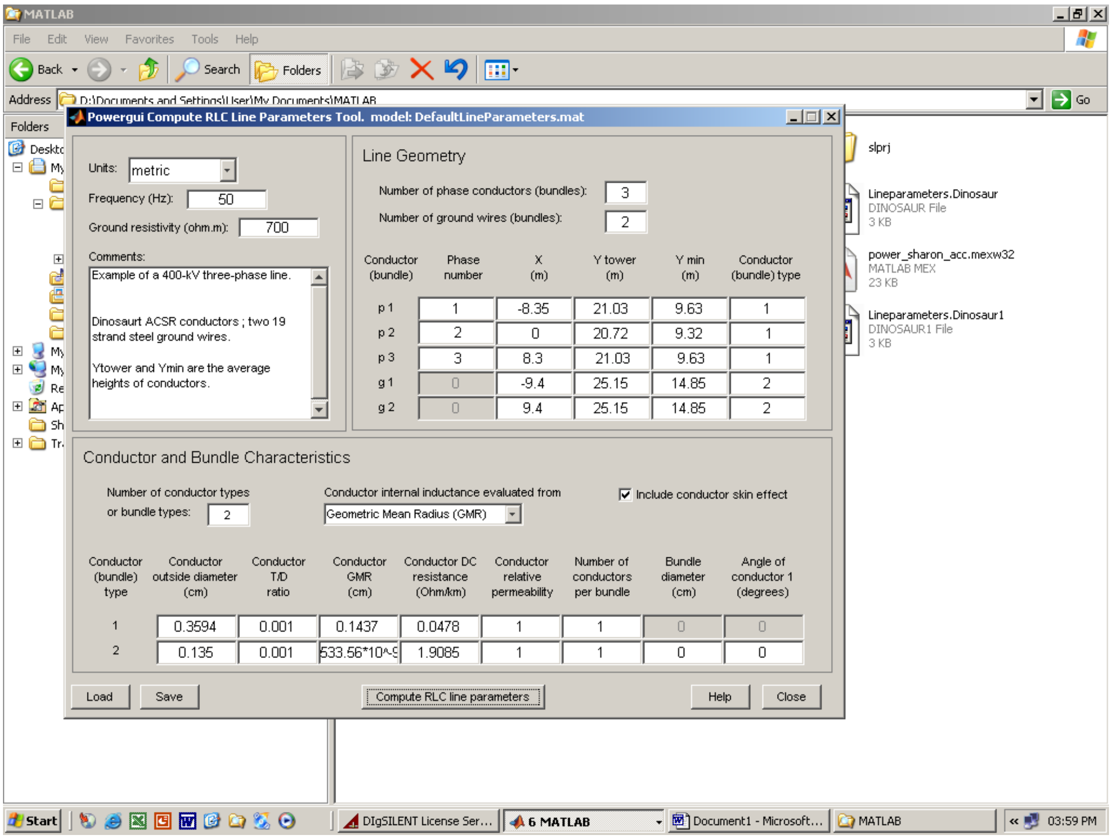
ii) PowerFactory conductor results file 1.pdf

iii) PowerFactory Dinosaur conductor model.pdf

iv) PowerFactory earth-wire results file.pdf

v) PowerFactory tower geometry.pdf


untitled *
File Edit View Simulation Format Tools Help
10.0
Normal
Powergui Compute RLC Line Parameters Tool. model: DefaultLineParameters.mat
Units: metric
Frequency (Hz): 50
Ground resistivity (ohm.m): 700
Comments:
Example of a 400-kV three-phase line.
Dinosaurt ACSR conductors ; two 19 strand steel ground wires.
Ytower and Ymin are the average heights of conductors.
Line Geometry
Number of phase conductors (bundles): 3
Number of ground wires (bundles): 2
Conductor (bundle) | Phase number | X (m) | Y tower (m) | Y min (m) | Conductor (bundle) type
p 1 | 1 | -8.2 | 21 | 9.6 | 1
p 2 | 2 | 0 | 21 | 9.6 | 1
p 3 | 3 | 8.2 | 21 | 9.6 | 1
g 1 | 0 | -8.3 | 26.25 | 15.95 | 2
g 2 | 0 | 8.3 | 26.25 | 15.95 | 2
Conductor and Bundle Characteristics
Number of conductor types or bundle types: 2
Conductor internal inductance evaluated from Geometric Mean Radius (GMR)
Include conductor skin effect
Conductor (bundle) type | Conductor outside diameter (cm) | Conductor T/D ratio | Conductor GMR (cm) | Conductor DC resistance (Ohm/km) | Conductor relative permeability | Number of conductors per bundle | Bundle diameter (cm) | Angle of conductor 1 (degrees)
1 | 0.3594 | 0.001 | 0.144 | 0.0478 | 1 | 1 | 0 | 0
2 | 0.135 | 0.001 | 0.00 | 1.9085 | 696.3 | 1 | 0 | 0
Load
Save
Compute RLC line parameters
Help
Close
Ready
100%
ode45
Start
DIgSILENT L...
MATLAB 7....
untitled *
untitled/po...
Powergui C...
About Simulink
03:25 PM


MATLAB
File Edit View Favorites Tools Help
Back
Search
Folders
Address D:\Documents and Settings\User\My Documents\MATLAB
Go
Folders
Powergui Compute RLC Line Parameters Tool. model: DefaultLineParameters.mat
Units: metric
Frequency (Hz): 50
Ground resistivity (ohm.m): 700
Comments:
Example of a 400-kV three-phase line.
Dinosaurt ACSR conductors ; two 19 strand steel ground wires.
Ytower and Ymin are the average heights of conductors.
Line Geometry
Number of phase conductors (bundles): 3
Number of ground wires (bundles): 2
Conductor (bundle) | Phase number | X (m) | Y tower (m) | Y min (m) | Conductor (bundle) type
p 1 | 1 | -8.35 | 21.03 | 9.63 | 1
p 2 | 2 | 0 | 20.72 | 9.32 | 1
p 3 | 3 | 8.3 | 21.03 | 9.63 | 1
g 1 | 0 | -9.4 | 25.15 | 14.85 | 2
g 2 | 0 | 9.4 | 25.15 | 14.85 | 2
Conductor and Bundle Characteristics
Number of conductor types or bundle types: 2
Conductor internal inductance evaluated from Geometric Mean Radius (GMR)
Include conductor skin effect
Conductor (bundle) type | Conductor outside diameter (cm) | Conductor T/D ratio | Conductor GMR (cm) | Conductor DC resistance (Ohm/km) | Conductor relative permeability | Number of conductors per bundle | Bundle diameter (cm) | Angle of conductor 1 (degrees)
1 | 0.3594 | 0.001 | 0.1437 | 0.0478 | 1 | 1 | 0 | 0
2 | 0.135 | 0.001 | 533.56*10^-9 | 1.9085 | 1 | 1 | 0 | 0
Load
Save
Compute RLC line parameters
Help
Close
slprj
Lineparameters.Dinosaur
DINOSAUR File
3 KB
power_sharon_acc.mexw32
MATLAB MEX
23 KB
Lineparameters.Dinosaur1
DINOSAUR1 File
3 KB
Start
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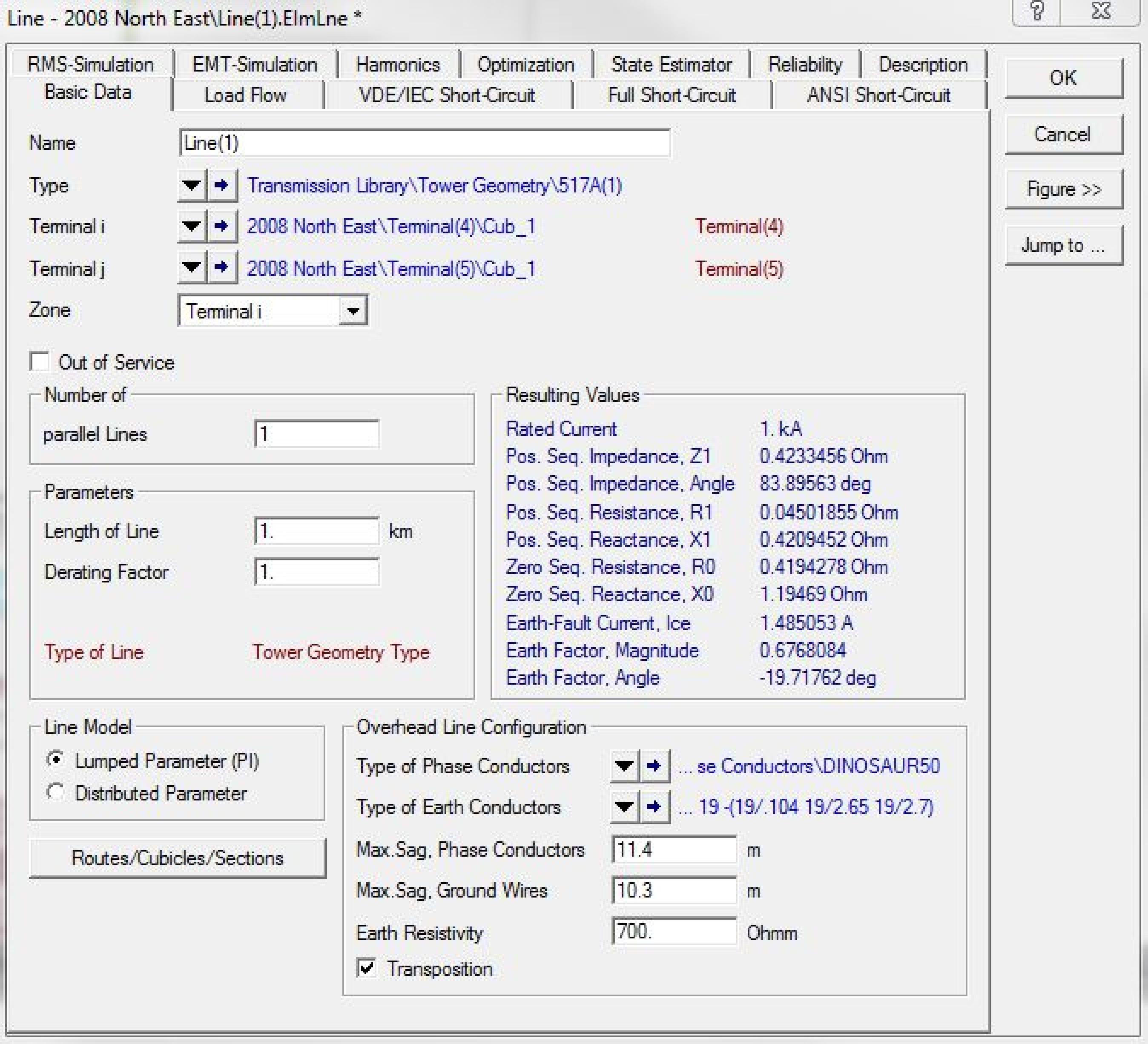
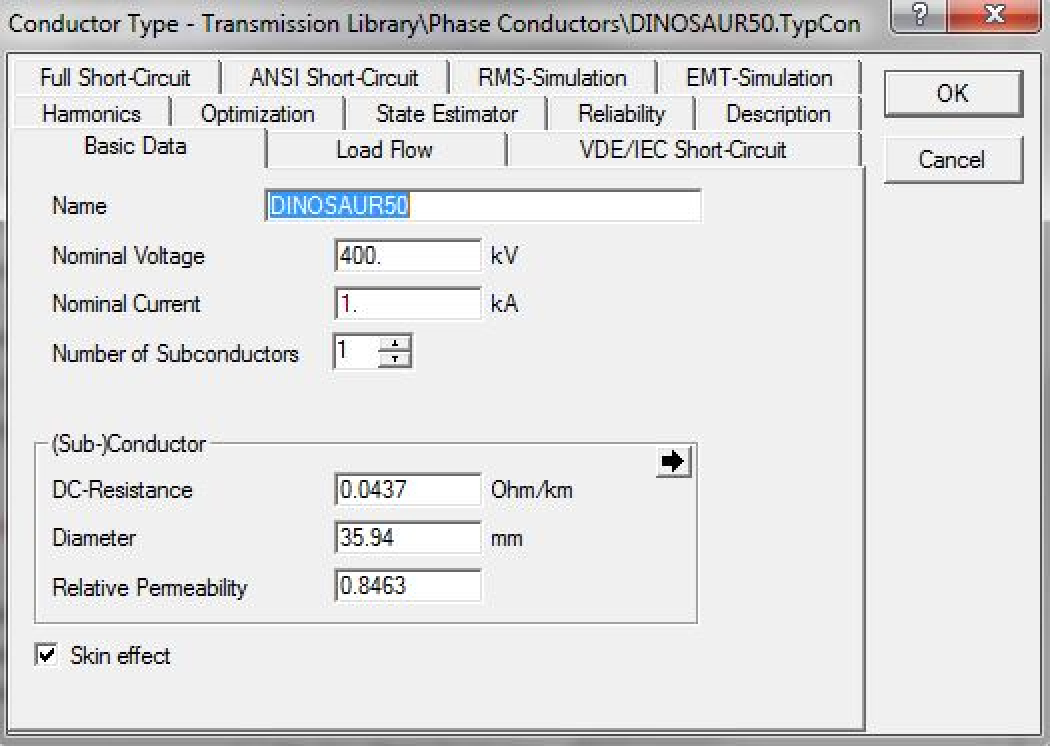
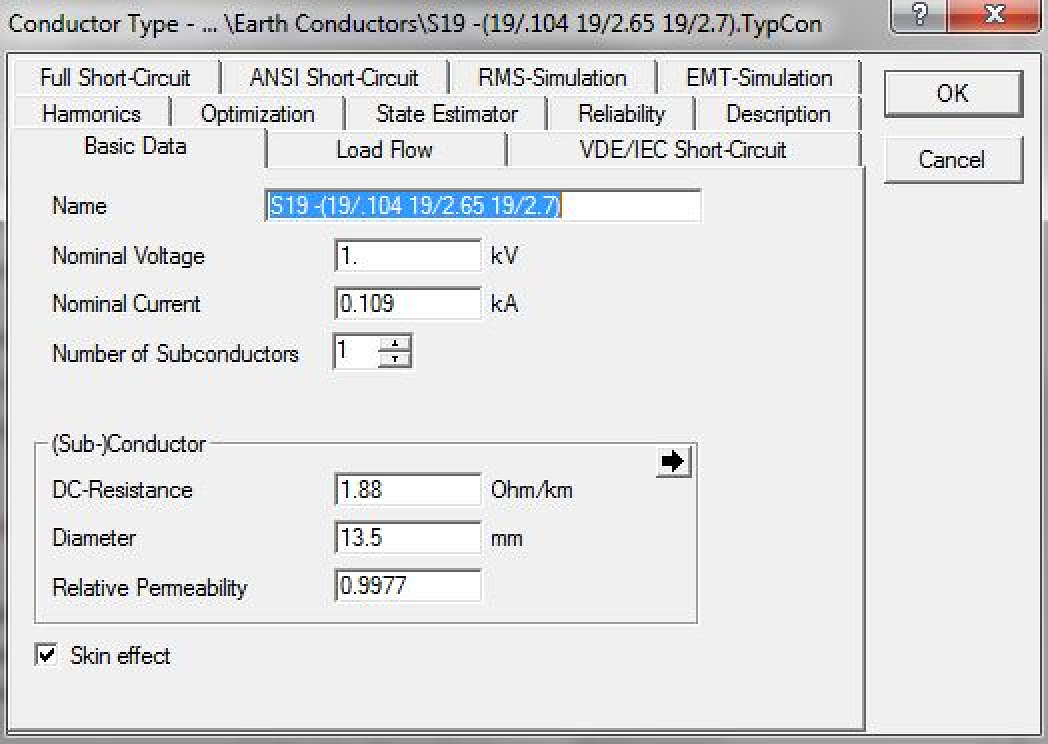
6 MATLAB
Document1 - Microsoft...
MATLAB
03:59 PM


Line - 2008 North East\Line(1).ElmLne *
RMS-Simulation
EMT-Simulation
Harmonics
Optimization
State Estimator
Reliability
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
Full Short-Circuit
ANSI Short-Circuit
OK
Cancel
Figure >>
Jump to ...
Name
Line(1)
Type
Transmission Library\Tower Geometry\517A(1)
Terminal i
2008 North East\Terminal(4)\Cub_1
Terminal(4)
Terminal j
2008 North East\Terminal(5)\Cub_1
Terminal(5)
Zone
Terminal i
Out of Service
Number of
parallel Lines
1
Parameters
Length of Line
1.
km
Derating Factor
1.
Type of Line
Tower Geometry Type
Resulting Values
Rated Current
1. kA
Pos. Seq. Impedance, Z1
0.4233456 Ohm
Pos. Seq. Impedance, Angle
83.89563 deg
Pos. Seq. Resistance, R1
0.04501855 Ohm
Pos. Seq. Reactance, X1
0.4209452 Ohm
Zero Seq. Resistance, R0
0.4194278 Ohm
Zero Seq. Reactance, X0
1.19469 Ohm
Earth-Fault Current, Ice
1.485053 A
Earth Factor, Magnitude
0.6768084
Earth Factor, Angle
-19.71762 deg
Line Model
Lumped Parameter (PI)
Distributed Parameter
Routes/Cubicles/Sections
Overhead Line Configuration
Type of Phase Conductors
... se Conductors\DINOSAUR50
Type of Earth Conductors
... 19 -(19/.104 19/2.65 19/2.7)
Max.Sag, Phase Conductors
11.4
m
Max.Sag, Ground Wires
10.3
m
Earth Resistivity
700.
Ohmm
Transposition



Conductor Type - Transmission Library\Phase Conductors\DINOSAUR50.TypCon
Full Short-Circuit
ANSI Short-Circuit
RMS-Simulation
EMT-Simulation
Harmonics
Optimization
State Estimator
Reliability
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
OK
Cancel
Name
DINOSAUR50
Nominal Voltage
400.
kV
Nominal Current
1.
kA
Number of Subconductors
1
(Sub-)Conductor
DC-Resistance
0.0437
Ohm/km
Diameter
35.94
mm
Relative Permeability
0.8463
Skin effect


Conductor Type - ... \Earth Conductors\S19 -(19/.104 19/2.65 19/2.7).TypCon
Full Short-Circuit
ANSI Short-Circuit
RMS-Simulation
EMT-Simulation
Harmonics
Optimization
State Estimator
Reliability
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
OK
Cancel
Name
S19 -(19/.104 19/2.65 19/2.7)
Nominal Voltage
1.
kV
Nominal Current
0.109
kA
Number of Subconductors
1
(Sub-)Conductor
DC-Resistance
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Ohm/km
Diameter
13.5
mm
Relative Permeability
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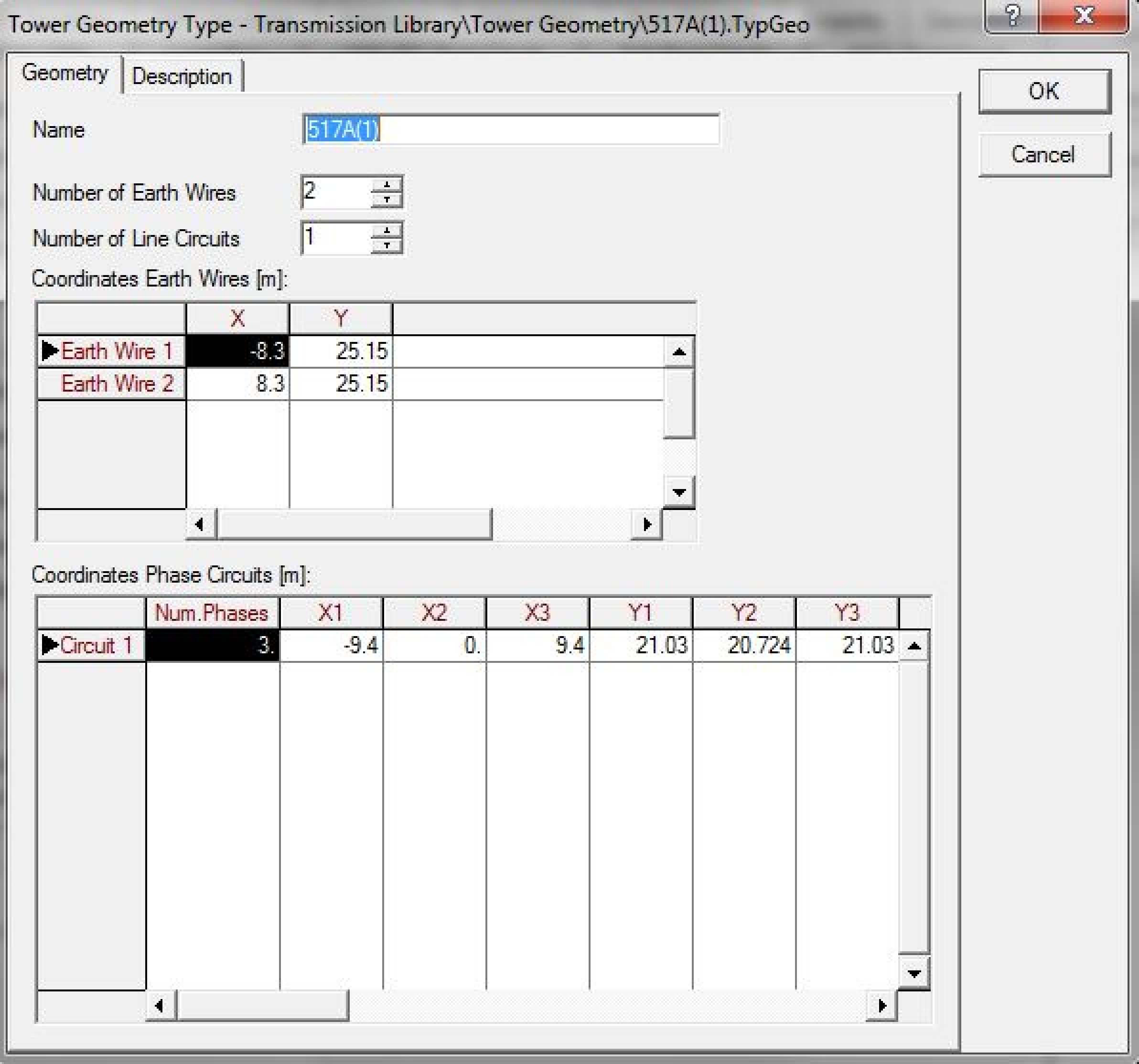
Skin effect



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Geometry
Description
OK
Cancel
Name
517A(1)
Number of Earth Wires
2
Number of Line Circuits
1
Coordinates Earth Wires [m]:
X
Y
Earth Wire 1
-8.3
25.15
Earth Wire 2
8.3
25.15
Coordinates Phase Circuits [m]:
Num.Phases
X1
X2
X3
Y1
Y2
Y3
Circuit 1
3.
-9.4
0.
9.4
21.03
20.724
21.03

Appendix Q

The following results files can be found in this appendix:

i) EMTP conductor calc_4.2 rev 3.4.pdf

ii) PowerFactory conductor impedance results.pdf

iii) PowerFactory earth-wire values.pdf

iv) PowerFactory phase conductor values.pdf

v) Tower geometry information.pdf

Series Self Impedance of a single conductor with earth return.

System Frequency

$f := 50Hz$

$\omega := 2\cdot\pi\cdot f$

GMR for Stranded Dinosaur Conductor taking Metal Resitivity into account.

Conductor values entered in milimeters and conductor clearances in meters.

Number of strands in the Steel-core.

$n_s := 19$

Steel Strand Diameter

$d_{ss} := 2.36mm$

$$r_s := \frac{d_{ss}}{2mm}$$

Aluminium Strand Diameter

$d_{aL} := 3.95mm$

$$r_{al} := \frac{d_{aL}}{2mm}$$

Conductor Diameter

$d_c := 35.94mm$

Conductor Radius

$$r_c := \frac{d_c}{2mm}$$

$r_c = 17.97$

Number of strands in first steel layer

$n_{s1} := 6$

Number of strands in second steel layer

$n_{s2} := 12$

Number of strands in first aluminium layer

$n_j := 12$

Number of strands in second aluminium layer

$n_k := 18$

Number of strands in third aluminium layer

$n_L := 24$

Total number of Aluminium strands in Conductor

$n_{al} := n_j + n_k + n_L$

$n_{al} = 54$

Permeability of steel

$\mu_s := 521.50438 \cdot 10^{-6} \cdot H \cdot m^{-1}$

Permeability of aluminium

$\mu_{al} := 4\pi \cdot 10^{-7} \cdot H \cdot m^{-1}$

Permeability of air

$\mu_0 := 4\pi \cdot 10^{-7} H \cdot m^{-1}$

Relative Permeability of steel

$\mu_{r\_s} := \frac{\mu_s}{\mu_0}$

$\mu_{r\_s} = 415$

GMR of single steel strand D_{ss}.

$$D_{ss} := r_s \cdot e^{-\frac{\mu_{r\_s}}{4}}$$

$$D_{ss} = 1.0323561580048832 \times 10^{-45}$$

Total GMR for the steel core with one centre strand and two layers

Distance calculations between strand in first steel layer and other strands in same layer

Number of strands in first steel layer

$$n_{s1} = 6$$

Number assignment to first strand in first steel layer

$$is := 2$$

Number series for other strands in first steel layer

$$jjs := is + 1 .. n_{s1} + 1$$

Angle between centre strand and two successive strands within first steel layer.

$$\alpha_{s1} := \frac{2\pi}{n_{s1} \cdot deg}$$

$$\alpha_{s1} = 60$$

$$d_{SL1} := \left[\prod_{k=1}^{(n_{s1}-1)} \sqrt{(2r_s)^2 + (2r_s)^2 - 2 \cdot (2r_s) \cdot (2r_s) \cdot \cos(k\, \alpha_{s1} \cdot deg)} \right]^{\left(\frac{n_{s1}}{n_s}\right)}$$

$$d_{SL1} = 6.831882675163027 \times 10^{0}$$

Number of strands in second steel layer

$$n_{s2} = 12$$

Number assignment to first strand in second steel layer

$is2 := 8$

Number series for other strands in second steel layer

$jjs := is2 + 1 .. n_s$

Angle between centre strand and two successive strands within second steel layer.

$$\alpha_{s2} := \frac{2\pi}{n_{s2} \cdot deg}$$

$\alpha_{s2} = 30$

Distance calculations between 1 strand in steel layer 2 and other strands in same layer

$$d_{SL2} := \left[\prod_{k=1}^{(n_{s2}-1)} \sqrt{(4r_s)^2 + (4r_s)^2 - 2 \cdot (4r_s) \cdot (4r_s) \cdot \cos(k\,\alpha_{s2} \cdot deg)} \right]^{\left(\frac{n_{s2}}{n_s}\right)}$$

$d_{SL2} = 231.05294815176742 \times 10^3$

Product of Distances between first and Second Steel layers

$$d_{SL1\_2} := \left[\prod_{k=1}^{n_{s2}} \sqrt{(2r_s)^2 + (4r_s)^2 - 2 \cdot (2r_s) \cdot (4r_s) \cdot \cos(k\,\alpha_{s2} \cdot deg)} \right]^{\frac{n_{s1}}{n_s}}$$

$d_{SL1\_2} = 357.97440969562405 \times 10^0$

Product of Distances between Second and First Steel layers

$$d_{SL2\_1} := \left[\prod_{k=1}^{n_{s1}} \sqrt{(2r_s)^2 + (4r_s)^2 - 2 \cdot (2r_s) \cdot (4r_s) \cdot \cos(k\,\alpha_{s1} \cdot deg)} \right]^{\frac{n_{s2}}{n_s}}$$

$d_{SL2\_1} = 354.458856$

Product of distances between First Steel Layer and Centre strand

$$d_{SL1\_C} := (2r_s)^{\left(\frac{n_{s1}}{n_s}\right)}$$

$$d_{SL1\_C} = 1.3114800396778374 \times 10^{0}$$

Product of distances between Second Steel Layer and Centre strand

$$d_{SL2\_C} := (4r_s)^{\left(\frac{n_{s2}}{n_s}\right)}$$

$$d_{SL2\_C} = 2.6646954360176722 \times 10^{0}$$

Product of distances between centre strand and first steel layer

$$d_{SC\_1} := (2r_s)^{\left(\frac{n_{s1}}{n_s}\right)}$$

$$d_{SC\_1} = 1.3114800396778374 \times 10^{0}$$

Product of distances between centre strand and second steel layer

$$d_{SC\_2} := (4r_s)^{\left(\frac{n_{s2}}{n_s}\right)}$$

$$d_{SC\_2} = 2.6646954360176722 \times 10^{0}$$

$$GMR_{ss} := \sqrt[n_s]{D_{ss} \cdot d_{SL1} \cdot d_{SL2} \cdot d_{SL1\_2} \cdot d_{SL2\_1} \cdot d_{SL1\_C} \cdot d_{SL2\_C} \cdot d_{SC\_1} \cdot d_{SC\_2}}$$

$$GMR_{ss} = 19.2456 \times 10^{-3}$$

The above calculations for the geometric Mean Radius for steel obtains an overall GMR value of near zero. This clearly shows that the steel core of an ACSR conductor can be ignored when determining the GMR for this type of conductor. The steel strands are therefore ignored due to their hvery high resistivity. The impact on the conductor inductive reactance would therefore also be neglectable.

Calculating the conductor GMR for the Aluminium Layers.

it is important to note from the equation above and those given for bundle conductors that the GMR for each strand is multiplied by itself for the number of strands in the conductor, provided that all strands has the same GMR. As shown above the GMR for the steel strands are ignored, since for all practical purposes this equates to zero..

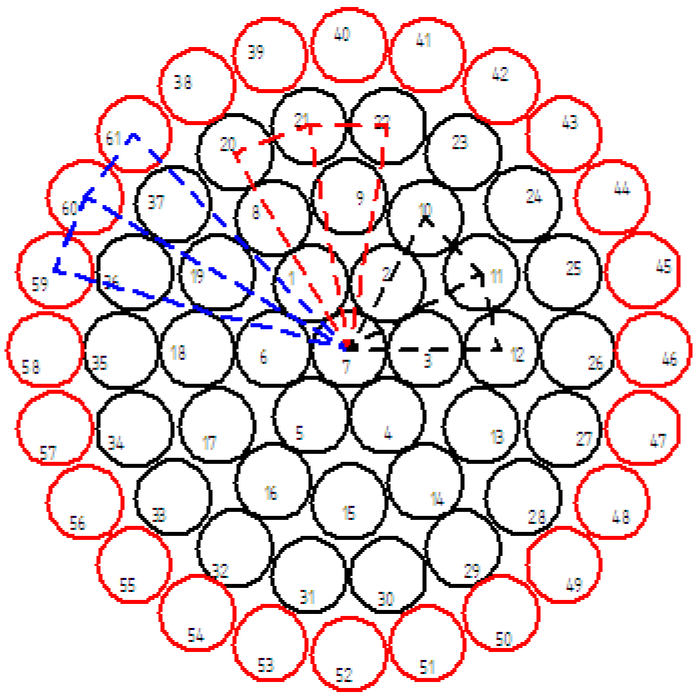


Figure 1: Method for determining distances between strands within a conductor

GMR for single aluminium strand (D_{s_al}).

Relative permeability of aluminium

$$\mu_{r\_al} := \frac{\mu_{al}}{\mu_0}$$

$$\mu_{r\_al} = 1$$

$$D_{s\_al} := r_{al} \cdot e^{-\frac{\mu_{r\_al}}{4}}$$

$$D_{s\_al} = 1.538132$$

Defining the distances between strands within the first aluminium layer

Number of strands in first aluminium layer

$n_j = 12$

Number assignment to first strand in first aluminium layer

$ij := 20$

Number series for other strands in first aluminium layer

$jj := ij + 1 .. \left(n_j + n_s\right)$

Angle between centre strand and two successive strands within first aluminium layer.

$$\alpha_1 := \frac{2\pi}{n_j \cdot deg}$$

$\alpha_1 = 30$

Distance calculations between 1 strand in layer and other strands in same layer

$$d_{al_{20,21}} := \sqrt{\left(5r_s + r_{al}\right)^2 + \left(5r_s + r_{al}\right)^2 - 2\cdot\left(5r_s + r_{al}\right)\cdot\left(5r_s + r_{al}\right)\cdot\cos\left(\alpha_1 \cdot deg\right)}$$

$d_{al_{20,21}} = 4.0764$

$$d_{al_{20,22}} := \sqrt{\left(5r_s + r_{al}\right)^2 + \left(5r_s + r_{al}\right)^2 - 2\cdot\left(5r_s + r_{al}\right)\cdot\left(5r_s + r_{al}\right)\cdot\cos\left(2\alpha_1 \cdot deg\right)}$$

$d_{al_{20,22}} = 7.875$

$$d_{al_{20,23}} := \sqrt{\left(5r_s + r_{al}\right)^2 + \left(5r_s + r_{al}\right)^2 - 2\cdot\left(5r_s + r_{al}\right)\cdot\left(5r_s + r_{al}\right)\cdot\cos\left(3\alpha_1 \cdot deg\right)}$$

$d_{al_{20,23}} = 11.1369$

$$d_{al_{20,24}} := \sqrt{\left(5r_s + r_{al}\right)^2 + \left(5r_s + r_{al}\right)^2 - 2\cdot\left(5r_s + r_{al}\right)\cdot\left(5r_s + r_{al}\right)\cdot\cos\left(4\alpha_1 \cdot deg\right)}$$

$d_{al_{20,24}} = 13.6399$

$$d_{al_{20,25}} := \sqrt{(5r_s + r_{al})^2 + (5r_s + r_{al})^2 - 2\cdot(5r_s + r_{al})\cdot(5r_s + r_{al})\cdot\cos(5\alpha_1\cdot deg)}$$

$$d_{al_{20,25}} = 15.2133$$

$$d_{al_{20,26}} := \sqrt{(5r_s + r_{al})^2 + (5r_s + r_{al})^2 - 2\cdot(5r_s + r_{al})\cdot(5r_s + r_{al})\cdot\cos(6\alpha_1\cdot deg)}$$

$$d_{al_{20,26}} = 15.75$$

$$d_{al_{20,27}} := \sqrt{(5r_s + r_{al})^2 + (5r_s + r_{al})^2 - 2\cdot(5r_s + r_{al})\cdot(5r_s + r_{al})\cdot\cos(7\alpha_1\cdot deg)}$$

$$d_{al_{20,27}} = 15.2133$$

$$d_{al_{20,28}} := \sqrt{(5r_s + r_{al})^2 + (5r_s + r_{al})^2 - 2\cdot(5r_s + r_{al})\cdot(5r_s + r_{al})\cdot\cos(8\alpha_1\cdot deg)}$$

$$d_{al_{20,28}} = 13.6399$$

$$d_{al_{20,29}} := \sqrt{(5r_s + r_{al})^2 + (5r_s + r_{al})^2 - 2\cdot(5r_s + r_{al})\cdot(5r_s + r_{al})\cdot\cos(9\alpha_1\cdot deg)}$$

$$d_{al_{20,29}} = 11.1369$$

$$d_{al_{20,30}} := \sqrt{(5r_s + r_{al})^2 + (5r_s + r_{al})^2 - 2\cdot(5r_s + r_{al})\cdot(5r_s + r_{al})\cdot\cos(10\alpha_1\cdot deg)}$$

$$d_{al_{20,30}} = 7.875$$

$$d_{al_{20,31}} := \sqrt{(5r_s + r_{al})^2 + (5r_s + r_{al})^2 - 2\cdot(5r_s + r_{al})\cdot(5r_s + r_{al})\cdot\cos(11\alpha_1\cdot deg)}$$

$$d_{al_{20,31}} = 4.0764$$

Product of distances in first aluminium layer (j).

Method 1

$$d_{L1} := \left(\prod_{jj} d_{al_{ij,jj}}\right)^{\left(\frac{n_j}{n_{al}}\right)}$$

$$d_{L1} = 269.5583$$

Method 2

$$d_{al\_L1} := \left[\prod_{k=1}^{(n_j-1)} \sqrt{(5r_s + r_{al})^2 + (5r_s + r_{al})^2 - 2\cdot(5r_s + r_{al})\cdot(5r_s + r_{al})\cdot\cos(k\,\alpha_1\cdot deg)}\right]^{\left(\frac{n_j}{n_{al}}\right)}$$

$$d_{al\_L1} = 269.5583$$

Product of distances in second aluminium layer (k).

Number assignment for first strand in second aluminium layer

$$ik := n_j + n_s + 1$$

$$ik = 32$$

Number series for other strands in second aluminium layer

$$jk := ik + 1 .. (n_k + ik - 1)$$

Angle between centre strand and two successive strands within second aluminium layer.

$$\alpha_2 := \frac{360}{n_k}$$

$$\alpha_2 = 20$$

Distance calculations between 1 strand in second layer and other strands in same layer

$$d_{al_{32,33}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(1 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,33}} = 4.1068$$

$$d_{al_{32,34}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(2 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,34}} = 8.0888$$

$$d_{al_{32,35}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(3 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,35}} = 11.825$$

$$d_{al_{32,36}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(4 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,36}} = 15.2019$$

$$d_{al_{32,37}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(5 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,37}} = 18.117$$

$$d_{al_{32,38}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(6 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,38}} = 20.4815$$

$$d_{al_{32,39}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(7 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,39}} = 22.2237$$

$$d_{al_{32,40}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(8 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,40}} = 23.2907$$

$$d_{al_{32,41}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(9 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,41}} = 23.65$$

$$d_{al_{32,42}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(10 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,42}} = 23.2907$$

$$d_{al_{32,43}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(11 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,43}} = 22.2237$$

$$d_{al_{32,44}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(12 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,44}} = 20.4815$$

$$d_{al_{32,45}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(13 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,45}} = 18.117$$

$$d_{al_{32,46}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(14 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,46}} = 15.2019$$

$$d_{al_{32,47}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(15 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,47}} = 11.825$$

$$d_{al_{32,48}} := \sqrt{(5 \cdot r_s + 3r_{al})^2 + (5 \cdot r_s + 3r_{al})^2 - 2 \cdot (5 \cdot r_s + 3r_{al}) \cdot (5 \cdot r_s + 3r_{al}) \cdot \cos(16 \cdot \alpha_2 \cdot deg)}$$

$$d_{al_{32,48}} = 8.0888$$

$$d_{al_{32,49}} := \sqrt{\left(5\cdot r_s + 3r_{al}\right)^2 + \left(5\cdot r_s + 3r_{al}\right)^2 - 2\cdot\left(5\cdot r_s + 3r_{al}\right)\cdot\left(5\cdot r_s + 3r_{al}\right)\cdot\cos\left(17\cdot\alpha_2\cdot deg\right)}$$

$$d_{al_{32,49}} = 4.1068$$

Product of distances in second aluminium layer (j).

Method 1

$$d_{L2} := \left(\prod_{jk} d_{al_{ik,jk}}\right)^{\left(\frac{n_k}{n_{al}}\right)}$$

$$d_{L2} = 3.1451 \times 10^6$$

Method 2

$$d_{al\_L2} := \left[\prod_{k=1}^{\left(n_k-1\right)} \sqrt{\left(5\cdot r_s + 3r_{al}\right)^2 + \left(5\cdot r_s + 3r_{al}\right)^2 - 2\cdot\left(5\cdot r_s + 3r_{al}\right)\cdot\left(5\cdot r_s + 3r_{al}\right)\cdot\cos\left(k\,\alpha_2\cdot deg\right)}\right]^{\left(\frac{n_k}{n_{al}}\right)}$$

$$d_{al\_L2} = 3.1451 \times 10^6$$

Product of distances in third aluminium layer (L).

Number assignment for first strand in third aluminium layer

$$iL := n_j + n_s + n_k + 1$$

$$iL = 50$$

Number series for other strands in third aluminium layer

$$jL := iL + 1 \,..\left(n_L + iL - 1\right)$$

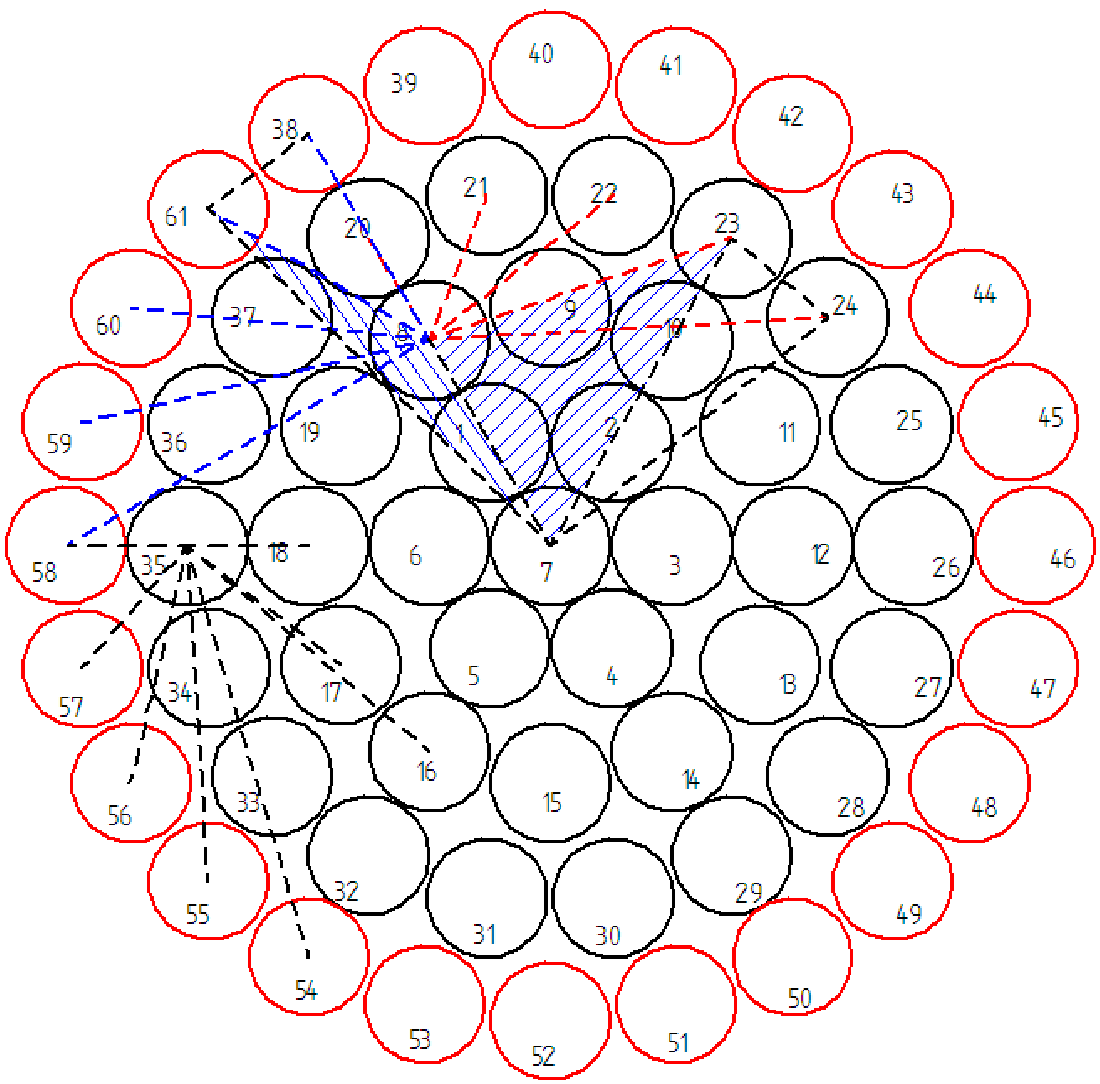
Angle between centre strand and two successive strands within third aluminium layer.

$$\alpha_3 := \frac{360}{n_L} \qquad \alpha_3 = 15$$

$$d_{al\_L3} := \left[\prod_{k=1}^{(n_L-1)} \sqrt{(5r_s + 5r_{al})^2 + (5r_s + 5r_{al})^2 - 2\cdot(5r_s + 5r_{al})\cdot(5r_s + 5r_{al})\cdot\cos(k\,\alpha_3\cdot deg)}\right]^{\left(\frac{n_L}{n_{al}}\right)}$$

$$d_{al\_L3} = 7.2333 \times 10^{12}$$

Product of distances between first and second aluminium layers.



$$d_{L1\_2} := \left[\prod_{k=1}^{n_k} \sqrt{\left(5r_s + 1r_{al}\right)^2 + \left(5r_s + 3r_{al}\right)^2 - 2\cdot\left(5r_s + 1r_{al}\right)\cdot\left(5r_s + 3r_{al}\right)\cdot\cos\left(k\,\alpha_2\cdot deg\right)}\right]^{\frac{n_j}{n_{al}}}$$

$$d_{L1\_2} = 19.5497 \times 10^3$$

Product of distances between first and third layer.

$$d_{L1\_3} := \left[\prod_{k=1}^{n_L} \sqrt{\left(5r_s + 1r_{al}\right)^2 + \left(5r_s + 5r_{al}\right)^2 - 2\cdot\left(5r_s + 1r_{al}\right)\cdot\left(5r_s + 5r_{al}\right)\cdot\cos\left(k\,\alpha_3\cdot deg\right)}\right]^{\left(\frac{n_j}{n_{al}}\right)}$$

$$d_{L1\_3} = 2.45 \times 10^6$$

Product of distances between second and first layer.

$$d_{L2\_1} := \left[\prod_{k=1}^{n_j} \sqrt{\left(5r_s + 3r_{al}\right)^2 + \left(5r_s + 1r_{al}\right)^2 - 2\cdot\left(5r_s + 3r_{al}\right)\cdot\left(5r_s + 1r_{al}\right)\cdot\cos\left(k\,\alpha_1\cdot deg\right)}\right]^{\frac{n_k}{n_{al}}}$$

$$d_{L2\_1} = 19.5029 \times 10^3$$

Product of distances between second and third layer.

$$d_{L2\_3} := \left[\prod_{k=1}^{n_L} \sqrt{\left(5r_s + 3r_{al}\right)^2 + \left(5r_s + 5r_{al}\right)^2 - 2\cdot\left(5r_s + 3r_{al}\right)\cdot\left(5r_s + 5r_{al}\right)\cdot\cos\left(k\,\alpha_3\cdot deg\right)}\right]^{\frac{n_k}{n_{al}}}$$

$$d_{L2\_3} = 3.8336 \times 10^9$$

Product of distances between third and first layer.

$$d_{L3\_1} := \left[\prod_{k=1}^{n_j} \sqrt{\left(5r_s + 5r_{al}\right)^2 + \left(5r_s + 1r_{al}\right)^2 - 2\cdot\left(5r_s + 5r_{al}\right)\cdot\left(5r_s + 1r_{al}\right)\cdot\cos\left(k\,\alpha_1\cdot deg\right)}\right]^{\frac{n_L}{n_{al}}}$$

$d_{L3\_1} = 2.4498 \times 10^6$

Product of distances between third and second layer.

$$d_{L3\_2} := \left[\prod_{k=1}^{n_k} \sqrt{\left(5r_s + 5r_{al}\right)^2 + \left(5r_s + 3r_{al}\right)^2 - 2\cdot\left(5r_s + 5r_{al}\right)\cdot\left(5r_s + 3r_{al}\right)\cdot\cos\left(k\,\alpha_2\cdot deg\right)}\right]^{\frac{n_L}{n_{al}}}$$

$d_{L3\_2} = 3.8254 \times 10^9$

Total Geometric Mean Radius

$$GMR_{al} := \sqrt[n_{al}]{D_{s\_al}\cdot d_{al\_L1}\cdot d_{al\_L2}\cdot d_{al\_L3}\cdot d_{L1\_2}\cdot d_{L1\_3}\cdot d_{L2\_1}\cdot d_{L2\_3}\cdot d_{L3\_1}\cdot d_{L3\_2}}$$

$GMR_{al} = 14.3686$

Total GMR of Conductor (GMR_{AL} + GMR_S)

$GMR_T := GMR_{al} + GMR_{ss}$

$GMR_T = 14.3879$

(An insignificant change)

Ratio of GMR against Radius of Conductor

$r_c = 17.97$

$$\frac{GMR_{al}}{\left(r_c\right)} = 799.5899 \times 10^{-3}$$

Generic Aproximated Method

$$GMR\_1 := r_c \cdot e^{-\left(\frac{\mu_{r\_al}}{4}\right)}$$

$$GMR\_1 = 13.995$$

Difference in GMR Calculations

$$GMR_{diff} := GMR_{al} - GMR\_1$$

$$GMR_{diff} = 0.3736$$

Bundle Radius (in mm)

$$r_b := 405$$

GMR of single stranded conductor

$$GMR_{al} = 14.3686$$

Number of subconductors per phase

$$n_{sc} := 1$$

GMR of Bundle Conductor

$$GMR_B := \sqrt[n_{sc}]{n_{sc} \cdot (GMR_{al}) \cdot r_b^{(n_{sc}-1)}}$$

$$GMR_B = 14.3686$$

Conductor Impedance Matrix Calculations

Conductor positions; Ankerlig to Koeberg line info from PowerFactory

$Ry := 21.03m$	$Rx := -9.4m$
$Wy := 20.724m$	$Wx := 0m$
$By := 21.03m$	$Bx := 9.4m$
$Ew1y := 25.15m$	$Ew1x := -8.3m$
$Ew2y := 25.15m$	$Ew2x := 8.3m$

Earth Wire Conductor Parameters

A 19 strand, 2.65 mm strand diameter earth wire is used.

(19/2.65)

Earth Wire Strand Diameter

$d_{ew} := 2.65mm$

Number of Earth Wire Layers

$N_{ewL} := 2$

Earth Wire Conductor Radius

$$r_{ew} := \left(\frac{d_{ew}}{2}\right)\cdot\left(2\cdot N_{ewL} + 1\right)$$

$r_{ew} = 6.625 \times 10^{-3} m$

Average height of conductor above ground = hi, hk, hj (hi = height at midspan +1/3 sag)

Average Height for Red-Phase

$h_{ci} := Ry$ conductor height at tower

$sag_i := 11.4m$

$$h_i := h_{ci} - sag_i + \left(\frac{1}{3}\right)\cdot sag_i$$

$h_i = 13.43\ m$

Average Height for White-Phase

$h_{ck} := Wy$

$sag_k := 11.4m$

$$h_k := h_{ck} - sag_k + \left(\frac{1}{3}\right)\cdot sag_k$$

$h_k = 13.12\ m$

Average Height for Blue-Phase

$h_{cj} := By$

$sag_j := 11.4m$

$h_j := h_{cj} - sag_j + \left(\frac{1}{3}\right) \cdot sag_j$

$h_j = 13.43\,m$

Average Height for Earth Wires 1 & 2

$h_v := Ew1y$

$sag_v := 10.3m$

$h_w := h_v - sag_v + \left(\frac{1}{3}\right) \cdot sag_v$

$h_v = 18.28\,m$

$h_w := h_v$

Horisontal Distances

Red to White (i;k)

$X_{ik} := |Rx| - |Wx|$

$X_{ik} = 9.4\,m$

Red to Blue (i;j)

$X_{ij} := |Rx| + Bx$

$X_{ij} = 18.8\,m$

Red to Earth Wire 1 (i;v)

$X_{iv} := |Rx| - |Ew1x|$

$X_{iv} = 1.1\,m$

Red to Earth Wire 2 (i;w)

$X_{iw} := |Rx| + Ew2x$

$X_{iw} = 17.7\,m$

White to Blue (k;j)

$X_{kj} := Wx + Bx$

$X_{kj} = 9.4\,m$

White to Red (k;i)

$X_{ki} := X_{ik}$

$X_{ki} = 9.4\,m$

White to Earth Wire 2 (k;w)

$X_{kw} := Wx + Ew2x$

$X_{kw} = 8.3\,m$

White to Earth Wire 1 (k;v)

$X_{kv} := |Ew1x| - Wx$

$X_{kv} = 8.3\,m$

Blue to Red Phase

$X_{ji} := X_{ij}$

$X_{ji} = 18.8\,m$

Blue to White Phase

$X_{jk} := X_{kj}$

$X_{jk} = 9.4\,m$

Blue to Earth Wire 2 (j;w)

$X_{jw} := Bx - |Ew2x|$

$X_{jw} = 1.1\,m$

Blue to Earth Wire 1 (j;v)

$X_{jv} := Bx + |Ew1x|$

$X_{jv} = 17.7\,m$

Horisontal distances

$X_i := Rx$

$X_v := Ew1x$

$X_w := Ew2x$

$X_j := Bx$

$X_k := Wx$

Diagonal Distances

Red Phase to Image of White Phase

$$D_{ik} := \sqrt{\left(h_i + h_k\right)^2 + X_{ik}^{\,2}}$$

$D_{ik} = 28.1687\,m$

Red Phase to Image of Blue Phase

$D_{ij} := \sqrt{\left(h_i + h_j\right)^2 + X_{ij}^{\ 2}}$

$D_{ij} = 32.7857\,m$

Red Phase to Image of Earth Wire 1

$D_{iv} := \sqrt{\left(h_i + h_v\right)^2 + X_{iv}^{\ 2}}$

$D_{iv} = 31.7324\,m$

Earth Wire 1 to Image of Red Phase

$D_{vi} := D_{iv}$

$D_{vi} = 31.7324\,m$

Red Phase to Image of Earth Wire 2

$D_{iw} := \sqrt{\left(h_i + h_w\right)^2 + X_{iw}^{\ 2}}$

$D_{iw} = 36.3184\,m$

Earth Wire 2 to Image of Red Phase

$D_{wi} := D_{iw}$

$D_{wi} = 36.3184\,m$

White Phase to Image of Red Phase

$D_{ki} := \sqrt{\left(h_k + h_i\right)^2 + X_{ik}^{\ 2}}$

$D_{ki} = 28.1687\,m$

White Phase to Image of Blue Phase

$D_{kj} := \sqrt{\left(h_k + h_j\right)^2 + X_{kj}^{\ 2}}$

$D_{kj} = 28.1687\,m$

White Phase to Image of Earth Wire 1

$D_{kv} := \sqrt{\left(h_k + h_v\right)^2 + X_{kv}^{\ 2}}$

$D_{kv} = 32.4855\,m$

Earth Wire 1 to Image of White Phase

$D_{vk} := D_{kv}$

$D_{vk} = 32.4855\,m$

White Phase to Image of Earth Wire 2

$D_{kw} := \sqrt{\left(h_k + h_w\right)^2 + X_{kw}^{\ 2}}$

$D_{kw} = 32.4855\,m$

Earth Wire 2 to Image of White Phase

$D_{wk} := D_{kw}$

$D_{wk} = 32.4855\,m$

Blue Phase to Image of White Phase

$D_{jk} := D_{ik}$

$D_{jk} = 28.1687\,m$

Blue Phase to Image of Red Phase

$D_{ji} := D_{ij}$

$D_{ji} = 32.7857\,m$

Blue Phase to Image of Earth Wire 1

$D_{jv} := D_{iw}$

$D_{jv} = 36.3184\,m$

Earth Wire 1 to Image of Blue Phase

$D_{vj} := D_{jv}$

$D_{vj} = 36.3184\,m$

Blue Phase to Image of Earth Wire 2

$D_{jw} := D_{iv}$

$D_{jw} = 31.7324\,m$

Earth Wire 2 to Image of Blue Phase

$D_{wj} := D_{jw}$

$D_{wj} = 31.7324\,m$

Earth Wire 1 to Image of Earth Wire 2

$$D_{vw} := \sqrt{\left(h_v + h_w\right)^2 + \left(\left|X_v\right| + \left|X_w\right|\right)^2}$$

$D_{vw} = 40.1582\,m$

Earth Wire 2 to Image of earth Wire 1

$$D_{wv} := \sqrt{\left(h_v + h_w\right)^2 + \left(\left|X_v\right| + \left|X_w\right|\right)^2}$$

$D_{wv} = 40.1582\,m$

Red Phase to White Phase

$$d_{ik} := \sqrt{\left(h_i - h_k\right)^2 + X_i^2}$$

$d_{ik} = 9.405\,m$

White Phase to Red Phase

$d_{ki} := d_{ik}$

Red Phase to Blue Phase

$$d_{ij} := \left|X_i\right| + X_j$$

$$d_{ij} = 18.8\,\text{m}$$

Blue Phase to Red Phase

$$d_{ji} := d_{ij}$$

Red Phase to Earth Wire 1

$$d_{iv} := \sqrt{\left(h_v - h_i\right)^2 + \left(\left|X_i\right| - \left|X_v\right|\right)^2}$$

$$d_{iv} = 4.9764\,\text{m}$$

Earth Wire 1 to Red Phase

$$d_{vi} := d_{iv}$$

Red Phase to Earth Wire 2

$$d_{iw} := \sqrt{\left(h_w - h_i\right)^2 + X_{iw}^{\,2}}$$

$$d_{iw} = 18.3533\,\text{m}$$

Earth Wire 2 to Red Phase

$$d_{wi} := d_{iw}$$

Blue to Red Phase

$$d_{ji} := \left|X_j\right| + \left|X_i\right|$$

$$d_{ji} = 18.8\,\text{m}$$

Blue to White Phase

$$d_{jk} := \sqrt{\left(h_j - h_k\right)^2 + X_j^{\,2}}$$

$$d_{jk} = 9.405\,\text{m}$$

Blue to Earth Wire 1

$$d_{jv} := \sqrt{\left(h_v - h_j\right)^2 + \left(\left|X_v\right| + X_j\right)^2}$$

$$d_{jv} = 18.3533\,\text{m}$$

Earth Wire 1 to Blue Phase

$$d_{vj} := d_{jv}$$

Blue to Earth Wire 2

$$d_{jw} := \sqrt{\left(h_w - h_j\right)^2 + \left(X_j - X_w\right)^2}$$

$$d_{jw} = 4.9764\,\text{m}$$

Earth Wire 2 to Blue Phase

$$d_{wj} := d_{jw}$$

White to red Phase

$$d_{ki} := \sqrt{{X_i}^2 + \left(h_i - h_k\right)^2}$$

$d_{ki} = 9.405\,m$

Red to White Phase

$d_{ik} = 9.405\,m$

White to Blue Phase

$$d_{kj} := \sqrt{{X_j}^2 + \left(h_j - h_k\right)^2}$$

$d_{kj} = 9.405\,m$

Blue to White Phase

$d_{jk} = 9.405\,m$

White to Earth Wire 1

$$d_{kv} := \sqrt{\left(h_v - h_k\right)^2 + {X_v}^2}$$

$d_{kv} = 9.7729\,m$

Earth Wire 1 to White Phase

$d_{vk} := d_{kv}$

White to Earth Wire 2

$$d_{kw} := \sqrt{\left(h_w - h_k\right)^2 + {X_w}^2}$$

$d_{kw} = 9.7729\,m$

Earth Wire 2 to White Phase

$d_{wk} := d_{kw}$

Earth Wire 1 to Earth Wire 2

$$d_{vw} := \left|X_v\right| + \left|X_w\right|$$

$d_{vw} = 16.6\,m$

Earth Wire 2 to Earth Wire 1

$d_{wv} := d_{vw}$

Mutual Impedance Angles

Red to Image of White Phase = Blue to Image of White Phase

$$\phi_{ik} := \frac{\operatorname{acos}\left(\dfrac{h_i + h_k}{D_{ik}}\right)}{deg}$$

$\phi_{ik} = 19.4937$

$\phi_{jk} := \phi_{ik}$

$\phi_{jk} = 19.4937$

Red to Image of Blue Phase = Blue to Image of Red Phase

$$\phi_{ij} := \frac{\operatorname{acos}\left(\frac{h_i + h_j}{D_{ij}}\right)}{deg} \qquad \phi_{ji} := \phi_{ij}$$

$\phi_{ij} = 34.9892$ $\qquad$ $\phi_{ji} = 34.9892$

Red to Image of Earth Wire 1 = Blue to Image of Earth Wire 2

$$\phi_{iv} := \frac{\operatorname{acos}\left(\frac{h_i + h_v}{D_{iv}}\right)}{deg} \qquad \phi_{jw} := \phi_{iv}$$

$\phi_{iv} = 1.9865$ $\qquad$ $\phi_{jw} = 1.9865$

Red to Image of Earth Wire 2 = Blue to Image of Earth Wire 1

$$\phi_{iw} := \frac{\operatorname{acos}\left(\frac{h_i + h_w}{D_{iw}}\right)}{deg} \qquad \phi_{jv} := \phi_{iw}$$

$\phi_{iw} = 29.167$ $\qquad$ $\phi_{jv} = 29.167$

White to Image of Red Phase

$$\phi_{ki} := \frac{\operatorname{acos}\left(\frac{h_k + h_i}{D_{ki}}\right)}{deg}$$

$\phi_{ki} = 19.4937$

White to Image of Blue Phase

$$\phi_{kj} := \frac{\operatorname{acos}\left(\frac{h_k + h_j}{D_{kj}}\right)}{deg}$$

$\phi_{kj} = 19.4937$

White to Image of Earth Wire 1

$$\phi_{kv} := \frac{\operatorname{acos}\left(\frac{h_k + h_v}{D_{kv}}\right)}{deg}$$

$$\phi_{kv} = 14.8031$$

White to Image of Earth Wire 2

$$\phi_{kw} := \frac{\operatorname{acos}\left(\frac{h_k + h_w}{D_{kw}}\right)}{deg}$$

$$\phi_{kw} = 14.8031$$

Earth Wire 1 to Image of Red

$$\phi_{vi} := \frac{\operatorname{acos}\left(\frac{h_v + h_i}{D_{vi}}\right)}{deg}$$

$$\phi_{vi} = 1.9865$$

Earth Wire 1 to Image of White

$$\phi_{vk} := \frac{\operatorname{acos}\left(\frac{h_v + h_k}{D_{vk}}\right)}{deg}$$

$$\phi_{vk} = 14.8031$$

Earth Wire 1 to Image of Blue

$$\phi_{vj} := \frac{\operatorname{acos}\left(\frac{h_v + h_j}{D_{vj}}\right)}{deg}$$

$$\phi_{vj} = 29.167$$

Earth Wire 1 to Image of Earth Wire 2

$$\phi_{vw} := \frac{\operatorname{acos}\left(\frac{h_v + h_w}{D_{vw}}\right)}{deg}$$

$\phi_{vw} = 24.4164$

Earth Wire 2 to Image of Red

$$\phi_{wi} := \frac{\operatorname{acos}\left(\frac{h_w + h_i}{D_{wi}}\right)}{deg}$$

$\phi_{wi} = 29.167$

Earth Wire 2 to Image of White

$$\phi_{wk} := \frac{\operatorname{acos}\left(\frac{h_w + h_k}{D_{wk}}\right)}{deg}$$

$\phi_{wk} = 14.8031$

Earth Wire 2 to Image of Blue

$$\phi_{wj} := \frac{\operatorname{acos}\left(\frac{h_w + h_j}{D_{wj}}\right)}{deg}$$

$\phi_{wj} = 1.9865$

Earth Wire 2 to Image of Earth Wire 1

$$\phi_{wv} := \frac{\operatorname{acos}\left(\frac{h_w + h_v}{D_{wv}}\right)}{deg}$$

$\phi_{wv} = 24.4164$

Permeability of Material at the same Flux Density

$$\mu_s = 521.5044 \times 10^{-6} \frac{m \cdot kg}{A^{2\times10^0} \cdot s^{2\times10^0}}$$

$$\mu_{al} = 1.2566 \times 10^{-6} \frac{m \cdot kg}{A^{2\times10^0} \cdot s^{2\times10^0}}$$

$$\mu o := 4 \cdot \pi \cdot 10^{-7} H \cdot m^{-1}$$

$$\mu o = 1.2566 \times 10^{-6} \frac{m \cdot kg}{A^{2\times10^0} \cdot s^{2\times10^0}}$$

It is clear from the above that the permeability of alumunium is equal to that of air.

Resistivity of Conductors and Earth

$\rho s := 1.0 \cdot 10^{-7} \Omega \cdot m$ Resistivity of steel.

$$\rho s = 0.0000001 \frac{m^3 \cdot kg}{A^2 \cdot s^3}$$

$\rho al := 2.82 \cdot 10^{-8} \Omega \cdot m$ Resistivity of aluminium.

$$\rho al = 0.0000000282 \frac{m^3 \cdot kg}{A^2 \cdot s^3}$$

$\rho e := 700 \Omega \cdot m$ Resistivity of earth.

Cross Sectional Area of Aluminium strands of Phase Conductor

$$A := \frac{\pi \cdot {d_{aL}}^2 \cdot n_{al}}{4}$$

$$A = 661.7254 \times 10^{-6} m^{2\times10^0}$$

Cross Sectional Area of Steel Strands of Earth Wire Conductor

Number of Steel Layers and Strands in Earth Wire

$SL_{ew} := 2$

$N_s := \left[\left(SL_{ew} + 1\right)6\right] + 1$

$N_s = 19$

$d_{aL} = 0.00395\,m$

$d_{ew} = 0.00265\,m$

$$A_s := \frac{\pi\cdot\left(d_{ew}\right)^2\cdot N_s}{4}$$

$A_s = 104.7937 \times 10^{-6}\,m^{2\times10^0}$

Radius of Earth Conductor

Number of strands in outer layer

$N_{so} := 12$

$$r_{ec} := \frac{d_{ew}}{2}\cdot\left(\frac{N_{so}}{3} + 1\right)$$

$r_{ec} = 6.625 \times 10^{-3}\,m$

Internal dc-Resistance

For ACSR conductor (Aluminium Conductor Steel Reinforced) the internal resistance of the steel section can be ignored, since the current will mostly flow in the aluminium strands.

Note: Since only the alumunium portion of the conductor is considered to conduct current by this method, only the area of the alumunium is used in the calculation.

Number of parallel conductors in bundle conductor

$N_b := 1$

DC-Resistance of Phase Conductor and Earth Wire at 20 degrees Celcius

(A simplified calculation, since equation 2.65 as obtained from the work done by [19] provides a more comprehensive calculation. This calculation takes into effect the impact of the actual lay length and the mean diameter of each stranded layer in the conductor.

Resistance calculated for a 1 km section.

Phase Conductor

$$R_{dc\_20} := \frac{\rho al \cdot 1km}{A \cdot N_b}$$

$$R_{dc\_20} = 0.0426\,\Omega$$

Earth Wire

$$R_{dcS\_20} := \frac{\rho s \cdot 1km}{A_s}$$

$$R_{dcS\_20} = 0.9543\,\Omega$$

DC-Resistance at Conductor Templated Temprature

$t_1 := 20$ degrees

$t_2 := 50$ degrees

Phase Conductor

$$R_{dc\_al} := \frac{(228.1 + t_2)}{(228.1 + t_1)} \cdot R_{dc\_20}$$

$$R_{dc\_al} = 0.0478\,\Omega$$

Earth Wire

$$R_{dc\_S} := \frac{(10 + t_2)}{(10 + t_1)} \cdot R_{dcS\_20}$$

$$R_{dc\_S} = 1.9085\,\Omega$$

Conductor AC-Resistance (approximated method)

Spiralling effect

$sp := 1.02$

Skin Effect

Determining the impact of frequency on conductor dc resistance

Radius of Steel and Aluminium Strands

$r_s = 1.18$

$r_{al} = 1.975$

Outer Radius of Conductor Steel Core

$$r_{s\_o} := r_s \cdot \left(\frac{12}{3} + 1\right)$$

$$r_{s\_o} = 5.9$$

Outer Radius of Conductor Aluminium portion

$$r_{al\_o} := r_{al} \cdot \left(\frac{24}{3} + 1\right)$$

$$r_{al\_o} = 17.775$$

Ratio of Steel Core Outer Radius to Outer Aluminium Radius

$$Ratio := \frac{r_{s\_o}}{r_{al\_o}}$$

$$Ratio = 0.331927$$

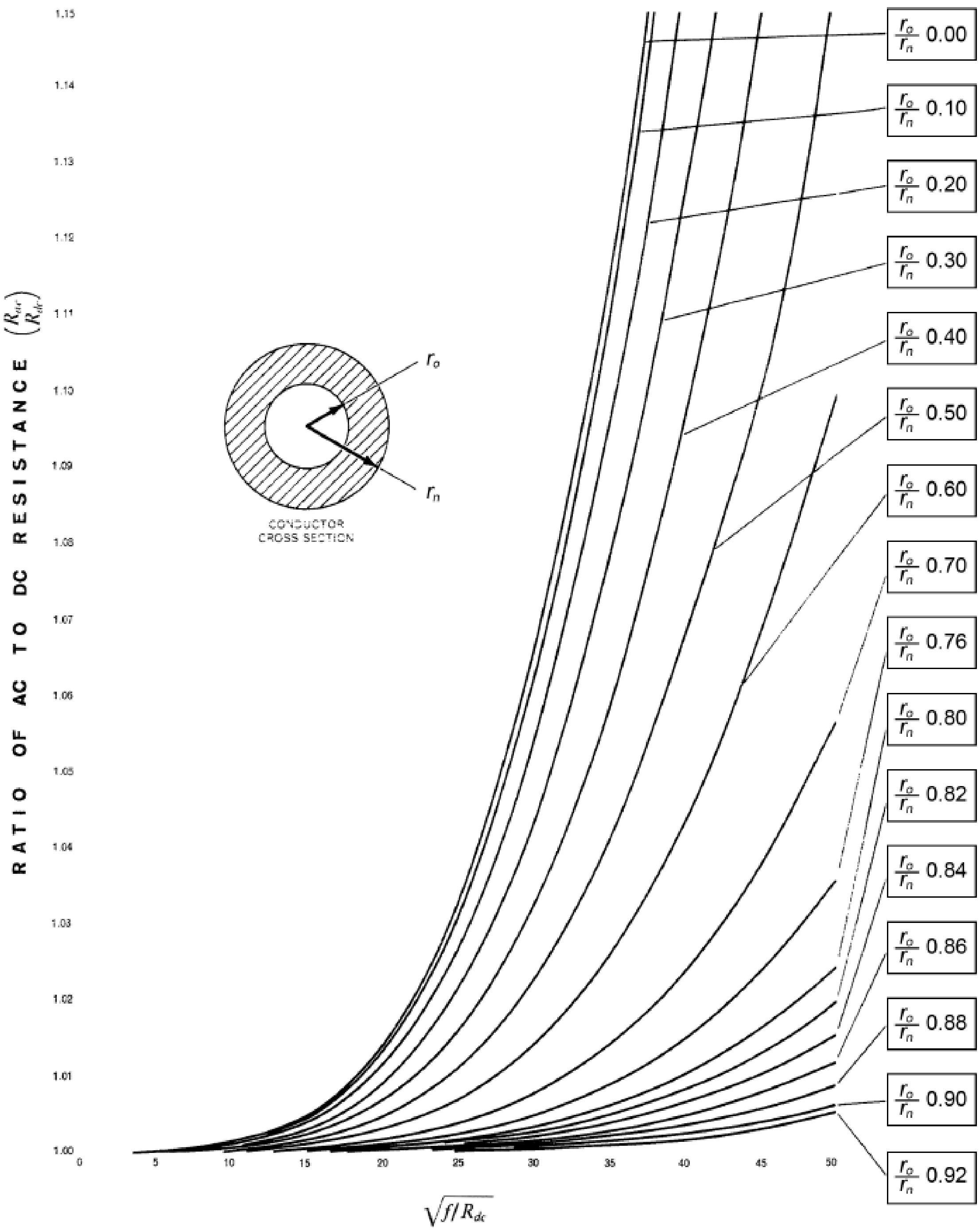
DC-Resistance of Aluminium portion of cable

$$R_{dc\_al} = 0.047769\,\Omega$$

Square root of Frequency/DC-Resistance Ratio

$$\sqrt{\frac{f}{R_{dc\_al}}} = 32.352828\,\frac{A \cdot s}{m \cdot kg^{0.5}}$$

Ratio of Rac/Rdc due to Skin effect from graph



$sk := 1.051$

Phase Conductor

$R_{ac\_al} := sp \cdot sk \cdot R_{dc\_al}$

$R_{ac\_al} = 0.0512\,\Omega$

Earth Wire

$R_{ac\_S} := sp \cdot R_{dc\_S}$

$R_{ac\_S} = 1.9467\,\Omega$

The conductor AC-Resistance is calculated in this example using standard conversion factors.

Internal Reactance of Phase Conductors according to Stephenson.

The internal reactance of all three phases are the same. Suffixes ii, kk and jj are used to indicate the self inductive reactance of the different phases.

$L_i := \frac{\mu_{al} \cdot 1km}{8 \cdot \pi}$

$\mu_{al} = 1.2566 \times 10^{-6} \frac{m \cdot kg}{A^{2 \times 10^0} \cdot s^{2 \times 10^0}}$

$L_i = 50 \times 10^{-6} H$ henries for 1 km length of conductor

$X_{ii} := 2 \cdot \pi \cdot f \cdot L_i$

$X_{ii} = 15.708 \times 10^{-3}\,\Omega$ Ω per km length of conductor

$X_{kk} := X_{ii}$

$X_{jj} := X_{ii}$

Phase Conductor Internal Reactance According to Carson

$r_c = 17.97$

$r_c \cdot e^{\frac{-1}{4}} = 13.9951 \times 10^0$

$Lc_i := \left(\frac{\mu o}{2 \cdot \pi}\right) \cdot \ln\left(\frac{r_c}{r_c \cdot e^{-\frac{1}{4}}}\right) \cdot 1km$ $\frac{GMD}{GMR}$

$Lc_i = 50 \times 10^{-6} H$

$Xc_{ii} := 2 \cdot \pi \cdot f \cdot Lc_i$

$Xc_{ii} = 15.708 \times 10^{-3}\,\Omega$ Ω per km length of conductor

Carson's equation provides the same answer as that used by William D. Stephenson.

Earth Wire Conductor Internal Reactance According to Stephenson

$L_{ewi} := \frac{\mu_s \cdot 1km}{8 \cdot \pi}$ $\mu_s = 5.215 \times 10^{-4} \frac{m \cdot kg}{A^2 \cdot s^2}$

$L_{ewi} = 20.75 \times 10^{-3} H$ henries for 1 km length of conductor

$X_{vv} := 2 \cdot \pi \cdot f \cdot L_{ewi}$

$X_{vv} = 6.5188\,\Omega$ Ω per km length of conductor

Earth Wire Conductor Internal Reactance According to Carson

$r_{ew} = 6.625 \times 10^{-3} m$ (Calculated radius)

$r_{ew} \cdot e^{\frac{-\mu_{r\_s}}{4}} = 5.796067412527417 \times 10^{-48} m$

$L_{ewi\_1} := \left(\frac{\mu_0}{2 \cdot \pi}\right) \cdot \ln\left(\frac{r_{ew}}{r_{ew} \cdot e^{-\frac{\mu_{r\_s}}{4}}}\right) \cdot 1km$ (Using approximated GMR of conductor)

$L_{ewi\_1} = 20.75 \times 10^{-3} H$

$X_{vv\_1} := 2 \cdot \pi \cdot f \cdot L_{ewi\_1}$

$X_{vv\_1} = 6.5188\,\Omega$ Ω per km length of conductor

$X_{ww} := X_{vv}$ earth wire 2 = earth wire 1

The same value is obtained with both calculation methods.

External Self Reactance for Red Phase Conductor, using Carson's method.

$r_c := r_c \cdot mm$

$$X_{ei} := 2\cdot\pi\cdot f\cdot\left(\frac{\mu o}{2\cdot\pi}\right)\cdot\ln\left(\frac{2\cdot h_i}{r_c}\right)\cdot 1km$$

$X_{ei} = 0.4593\,\Omega$ Ω per 1 km length of conductor

Self Reactance for Red Phase Conductor, using EPRI method excluding earth correction.

$D_{ii} := 2\cdot h_i = 26.86\,m$

$$X_{ei\_E} := 2\cdot\pi\cdot f\cdot\left(\frac{\mu o}{2\cdot\pi}\right)\cdot\ln\left(\frac{D_{ii}}{GMR_{al}\cdot mm}\right)\cdot 1km$$

$X_{ei\_E} = 0.4733\,\Omega$ Ω per 1 km length of conductor

OR

Involving the complex image depth as used in low frequency applications.

$\alpha 1 := \sqrt{\mu o\cdot\left(\frac{\omega}{\rho e}\right)}$ $\alpha 1 = 0.000751\,\frac{1}{m}$

$$p := \left(\frac{1}{\alpha 1}\right)\cdot e^{-45ideg}$$

$p = (941.5733 - 941.5733i)\,m$

External Part of Self Impedance

$$Z_{ii} := \left(\omega\cdot\frac{\mu o}{2\cdot\pi}\right)j\cdot\ln\left[\frac{2\cdot\left(p + h_i\right)}{r_c}\right]\cdot 1km$$

$Z_{ii} = (0.0489 + 0.7485i)\,\Omega$

Total Self Impedance without earth return

$Z_{ii\_tot} := Z_{ii} + j \cdot Xc_{ii}$

$Z_{ii\_tot} = (0.0489 + 0.7643i)\,\Omega$

Total Self Reactance for Red Phase Conductor, Carson method excluding earth correction factors

$X_{ti} := X_{ii} + X_{ei}$

$X_{ti} = 0.475\,\Omega$ Ω per 1 km length of conductor

External Self Reactance for White Phase Conductor Carsons Method

$$X_{ek} := 2 \cdot \pi \cdot f \cdot \left(\frac{\mu o}{2 \cdot \pi}\right) \cdot \ln\left(\frac{2 \cdot h_k}{r_c}\right) \cdot 1km$$

$X_{ek} = 0.4578\,\Omega$ Ω for 1 km length of conductor

Self Reactance for White Phase Conductor, using EPRI method excluding earth correction.

$D_{kk} := 2 \cdot h_k = 26.248\,m$

$$X_{ek\_E} := 2 \cdot \pi \cdot f \cdot \left(\frac{\mu o}{2 \cdot \pi}\right) \cdot \ln\left(\frac{D_{kk}}{GMR_{al} \cdot mm}\right) \cdot 1km$$

$X_{ek\_E} = 0.4719\,\Omega$ Ω per 1 km length of conductor

The internal conductor reactance is included in the EPRI equation

OR

Involving the complex image depth as used in low frequency applications.

$\alpha 1 := \sqrt{\mu o \cdot \left(\frac{\omega}{\rho e}\right)}$ $\alpha 1 = 0.000751 \frac{1}{m}$

$p := \left(\frac{1}{\alpha 1}\right) \cdot e^{-45 i deg}$

$p = (941.573341 - 941.573341i)\, m$

$Z_{kk} := \left(\omega \cdot \frac{\mu o}{2 \cdot \pi}\right) j \cdot \ln\left[\frac{2 \cdot (p + h_k)}{r_c}\right] \cdot 1km$

$Z_{kk} = (0.0489 + 0.7485i)\, \Omega$

$Z_{kk\_tot} := Z_{kk} + i \cdot X_{kk}$

$Z_{kk\_tot} = (0.0489 + 0.7642i)\, \Omega$

Total Self Reactance for White Phase Conductor, Carson method excluding earth correction factors

$X_{tk} := X_{kk} + X_{ek}$

$X_{tk} = 0.473541\, \Omega$ Ω per km

External Self Reactance for Blue Phase Conductor Carsons Method

$X_{ej} := 2 \cdot \pi \cdot f \cdot \left(\frac{\mu o}{2 \cdot \pi}\right) \cdot \ln\left(\frac{2 \cdot h_j}{r_c}\right) \cdot 1km$

$X_{ej} = 0.4593\, \Omega$ Ω for 1 km length of conductor

Self Reactance for Blue Phase Conductor, using EPRI method excluding earth correction.

$$D_{jj} := 2 \cdot h_j = 26.86\,m$$

$$X_{ej\_E} := 2 \cdot \pi \cdot f \cdot \left(\frac{\mu o}{2 \cdot \pi}\right) \cdot \ln\left(\frac{D_{jj}}{GMR_{al} \cdot mm}\right) \cdot 1km$$

$X_{ej\_E} = 0.4733\,\Omega$ Ω per 1 km length of conductor

The (internal + external) conductor reactance is included in the EPRI equation through the use of conductor GMR rather than radius. The exact same result as for the total self reactance for blue phase conductor is obtained when the GMR formula for a solid conductor is used in the above equation. See immediately below.

$$2 \cdot \pi \cdot f \cdot \left(\frac{\mu o}{2 \cdot \pi}\right) \cdot \ln\left(\frac{D_{jj}}{r_c \cdot e^{\frac{-1}{4}}}\right) \cdot 1km = 0.475\,\Omega$$

OR

Involving the complex image depth as used in low frequency applications.

$$\alpha 1 := \sqrt{\mu o \cdot \left(\frac{\omega}{\rho e}\right)} \qquad \alpha 1 = 0.000751 \frac{1}{m}$$

$$p := \left(\frac{1}{\alpha 1}\right) \cdot e^{-45ideg}$$

$$p = (941.57334 - 941.57334i)\,m$$

$$Z_{jj} := \left(\omega \cdot \frac{\mu o}{2 \cdot \pi}\right) j \cdot \ln\left[\frac{2 \cdot (p + h_j)}{r_c}\right] \cdot 1km$$

$$Z_{jj} = (0.0489 + 0.7485i)\,\Omega$$

$$Z_{jj\_tot} := Z_{jj} + i \cdot X_{jj}$$

$$Z_{jj\_tot} = (0.0489 + 0.7643i)\,\Omega$$

Total Self Reactance for Blue Phase Conductor, Carson method excluding earth correction factors

$X_{tj} := X_{jj} + X_{ej}$

$X_{tj} = 0.475\,\Omega$ — Ω per 1 km length of conductor

External Self Reactance for Earth Wire 1

$X_{e\_v} := 2\cdot\pi\cdot f\cdot\left(\frac{\mu o}{2\cdot\pi}\right)\cdot\ln\left(\frac{2\cdot h_v}{r_{ew}}\right)\cdot 1km$ — Carson's method

$X_{e\_v} = 0.5414\,\Omega$ — Ω for 1 km length of conductor

External Self Reactance for Earth Wire 2

$X_{e\_w} := 2\cdot\pi\cdot f\cdot\left(\frac{\mu o}{2\cdot\pi}\right)\cdot\ln\left(\frac{2\cdot h_w}{r_{ew}}\right)\cdot 1km$ — Carson's method

$X_{e\_w} = 0.5414\,\Omega$ — Ω for 1 km length of conductor

Total Self Reactance for Earth Wires

$X_{tv} := X_{vv} + X_{e\_v}$

$X_{tv} = 7.0602\,\Omega$

$X_{tw} := X_{ww} + X_{e\_w}$

$X_{tw} = 7.0602\,\Omega$

OR

Involving the complex image depth as used in low frequency applications.

$\alpha 1 := \sqrt{\mu o \cdot \left(\frac{\omega}{\rho e}\right)}$ $\alpha 1 = 0.000751 \frac{1}{m}$ $\rho e = 700 \frac{m^3 \cdot kg}{A^2 \cdot s^3}$

$p := \left(\frac{1}{\alpha 1}\right) \cdot e^{-45ideg}$

$p = (941.5733 - 941.5733i)\,m$

$Z_{ew} := \left(\omega \cdot \frac{\mu o}{2 \cdot \pi}\right) j \cdot \ln\left[\frac{2 \cdot (p + h_v)}{r_{ew}}\right] \cdot 1km$

$Z_{ew} = (0.0487 + 0.8114i)\,\Omega$

$Z_v := R_{ac\_S} + Z_{ew} + i \cdot X_{vv} = (1.9954 + 7.3302i)\,\Omega$

$Z_w := R_{ac\_S} + Z_{ew} + i \cdot X_{ww} = (1.9954 + 7.3302i)\,\Omega$

Carsons correction terms delta R and delta X

For the assumption of perfect conducting ground, P and Q = 0. For any other assumption P and Q can be calculated as follows;

Self Impedance

$\phi := 0 \cdot deg$ $\rho e = 700 \frac{m^3 \cdot kg}{A^2 \cdot s^3}$

$Z_{Eii} = 2 * (P + jQ)$

Self Impedance Correction Factors for Red Phase

$k_i := 4 \cdot \pi \cdot \sqrt{5} \cdot 10^{-4} \cdot \frac{2 \cdot h_i}{m} \cdot \sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega \cdot m}}}$; for k to be unitless

$$P_i := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_i\cdot\cos(\phi) + \frac{k_i^{\,2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_i}\right)\right)\cdot\cos(2\cdot\phi) + \phi\cdot\sin(2\cdot\phi)\right] + \frac{k_i^{\,3}\cdot\cos(3\cdot\phi)}{45\cdot\sqrt{2}}\cdot\right.$$

$P_i = 0.048767\,\Omega$

$$Q_i := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_i}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_i\cdot\cos(\phi) - \frac{\pi\cdot k_i^{\,2}\cdot\cos(2\cdot\phi)}{64} + \frac{k_i^{\,3}\cdot\cos(3\cdot\phi)}{45\cdot\sqrt{2}} - \frac{k_i^{\,4}}{384}\cdot\left[\left(\ln\left(\frac{2}{k_i}\right.\right.\right.\right.$$

$Q_i = 0.284559\,\Omega$

$\delta R_{ii} := P_i$ $\qquad\qquad$ $\delta X_{ii} := Q_i$

Self Impedance Correction Factors for White Phase

$$k_k := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{2\cdot h_k}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$; for k to be unitless

$$P_k := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_k\cdot\cos(\phi) + \frac{k_k^{\,2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_k}\right)\right)\cdot\cos(2\cdot\phi) + \phi\cdot\sin(2\cdot\phi)\right] + \frac{k_k^{\,3}\cdot\cos(3\cdot\phi}{45\cdot\sqrt{2}}\right.$$

$P_k = 0.04878\,\Omega$

$$Q_k := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_k}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_k\cdot\cos(\phi) - \frac{\pi\cdot k_k^{\,2}\cdot\cos(2\cdot\phi)}{64} + \frac{k_k^{\,3}\cdot\cos(3\cdot\phi)}{45\cdot\sqrt{2}} - \frac{k_k^{\,4}}{384}\cdot\left[\left(\ln\left(\right.\right.\right.\right.$$

$Q_k = 0.285994\,\Omega$

$\delta R_{kk} := P_k$ $\qquad\qquad$ $\delta X_{kk} := Q_k$

Self Impedance Correction Factors for Blue Phase

$$k_j := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{2\cdot h_j}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$; for k to be unitless

$$P_j := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_j\cdot\cos(\phi) + \frac{k_j^{\,2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_j}\right)\right)\cdot\cos(2\cdot\phi) + \phi\cdot\sin(2\cdot\phi)\right] + \frac{k_j^{\,3}\cdot\cos(3\cdot\phi)}{45\cdot\sqrt{2}}\cdot\right.$$

$$P_j = 0.048767\,\Omega$$

$$Q_j := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_j}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_j\cdot\cos(\phi) - \frac{\pi\cdot k_j^{\,2}\cdot\cos(2\cdot\phi)}{64} + \frac{k_j^{\,3}\cdot\cos(3\cdot\phi)}{45\cdot\sqrt{2}} - \frac{k_j^{\,4}}{384}\cdot\left[\left(\ln\left(\frac{2}{k_j}\right.\right.\right.\right.$$

$$Q_j = 0.284559\,\Omega$$

$\delta R_{jj} := P_j$ $\qquad\qquad$ $\delta X_{jj} := Q_j$

Self Impedance Correction Factors for Earth Wire 1 & 2

$$k_{ew} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{2\cdot h_v}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$; for k to be unitless

$$P_{ew} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{ew}\cdot\cos(\phi) + \frac{k_{ew}^{\,2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{ew}}\right)\right)\cdot\cos(2\cdot\phi) + \phi\cdot\sin(2\cdot\phi)\right] + \frac{k_{ew}^{\,3}\cdot}{4\ldots}\right.$$

$$P_{ew} = 0.048564\,\Omega$$

$$Q_{ew} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{ew}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{ew}\cdot\cos(\phi) - \frac{\pi\cdot k_{ew}^{\,2}\cdot\cos(2\cdot\phi)}{64} + \frac{k_{ew}^{\,3}\cdot\cos(3\cdot\phi)}{45\cdot\sqrt{2}} - \frac{k_{e\ldots}}{3\ldots}\right.$$

$$Q_{ew} = 0.26539\,\Omega$$

$\delta R_{vv} := P_{ew}$ $\qquad\qquad$ $\delta X_{vv} := Q_{ew}$

$\delta R_{ww} := P_{ew}$ $\qquad\qquad$ $\delta X_{ww} := Q_{ew}$

Total Self Impedance for Red Phase

Carson Method

$Z_{ii} := \left(R_{ac\_al} + \delta R_{ii}\right) + i\left(X_{ii} + X_{ei} + \delta X_{ii}\right)$

$Z_{ii} = (0.099977 + 0.759549i)\ \Omega$

EPRI Method

$Z_{EPRI\_R} := \left(R_{ac\_al} + \delta R_{ii}\right) + i\cdot\left(X_{ei\_E} + \delta X_{ii}\right)$

$Z_{EPRI\_R} = (0.099977 + 0.757894i)\ \Omega$

Complex Method

$Z_{CP\_R} := R_{ac\_al} + Z_{ii\_tot}$

$Z_{CP\_R} = (0.10011 + 0.76425i)\ \Omega$

Total Self Impedance for White Phase

Carson Method

$Z_{kk} := \left(R_{ac\_al} + \delta R_{kk}\right) + i\left(X_{kk} + X_{ek} + \delta X_{kk}\right)$

$Z_{kk} = (0.09999 + 0.75954i)\ \Omega$

EPRI Method

$Z_{EPRI\_W} := \left(R_{ac\_al} + \delta R_{kk}\right) + i\cdot\left(X_{ek\_E} + \delta X_{kk}\right)$

$Z_{EPRI\_W} = (0.09999 + 0.75788i)\ \Omega$

Complex Method

$Z_{CP\_W} := R_{ac\_al} + Z_{kk\_tot}$

$Z_{CP\_W} = (0.10012 + 0.76424i)\ \Omega$

Total Self Impedance for Blue Phase

Carson Method

$Z_{jj} := \left(R_{ac\_al} + \delta R_{jj}\right) + i\left(X_{jj} + X_{ej} + \delta X_{jj}\right)$

$Z_{jj} = (0.099977 + 0.759549i)\,\Omega$

EPRI Method

$Z_{EPRI\_B} := \left(R_{ac\_al} + \delta R_{ii}\right) + i\cdot\left(X_{ej\_E} + \delta X_{jj}\right)$

$Z_{EPRI\_B} = (0.099977 + 0.757894i)\,\Omega$

Complex Method

$Z_{CP\_B} := R_{ac\_al} + Z_{jj\_tot}$

$Z_{CP\_B} = (0.100112 + 0.764252i)\,\Omega$

Total Self Impedance for Earth Wires 1 & 2

Complex Image Method

$Z_{vv} := \left(R_{ac\_S} + \delta R_{vv}\right) + i\cdot\left(X_{vv} + X_{e\_v} + \delta X_{vv}\right)$

$Z_{vv} = (1.995246 + 7.325556i)\,\Omega$

$Z_{v} = (1.995426 + 7.330208i)\,\Omega$

$Z_{ww} := \left(R_{ac\_S} + \delta R_{ww}\right) + i\cdot\left(X_{ww} + X_{e\_w} + \delta X_{ww}\right)$

$Z_{ww} = (1.995246 + 7.325556i)\,\Omega$

$Z_{w} = (1.995426 + 7.330208i)\,\Omega$

Total Self Impedance for Line Assuming full Transposition (effect of earth wires are nulled).

$R_{tot\_ext} := R_{ac\_al} + \left(\frac{1}{3}\right)\cdot\left(\delta R_{ii} + \delta R_{kk} + \delta R_{jj}\right)$

$R_{tot\_ext} = 0.09998\,\Omega$

$\delta X_{tot} := \left(\frac{1}{3}\right)\cdot\left(\delta X_{ii} + \delta X_{kk} + \delta X_{jj}\right)$

$\delta X_{tot} = 0.28504\,\Omega$

$$X_{tot\_ext} := X_{ii} + 2\cdot\pi\cdot f\cdot\left(\frac{\mu o}{2\cdot\pi}\right)\cdot\ln\left(\frac{\sqrt[3]{D_{ik}\cdot D_{ij}\cdot D_{jk}}}{r_c}\right)\cdot 1km + \delta X_{tot}$$

$$X_{tot\_ext} = 0.766195\,\Omega$$

$$Z_{tot\_ext} := R_{tot\_ext} + i\cdot X_{tot\_ext}$$

$$Z_{tot\_ext} = (0.099981 + 0.766195i)\,\Omega \qquad \frac{(Z_{ii} + Z_{kk} + Z_{jj})}{3} = (0.099981 + 0.759544i)\,\Omega$$

Mutual Impedance

Mutual Impedance Red to White Phase

Earth Contribution

$$k_{ik} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{ik}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{ik} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{ik}\cdot\cos(\phi_{ik}\cdot deg) + \frac{k_{ik}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{ik}}\right)\right)\cdot\cos(2\cdot\phi_{ik}\cdot deg) + (\phi_{ik}\cdot deg)\cdot si\right.\right.$$

$$P_{ik} = 0.048772\,\Omega$$

$$Q_{ik} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{ik}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{ik}\cdot\cos(\phi_{ik}\cdot deg) - \frac{\pi\cdot k_{ik}^{2}\cdot\cos(2\cdot\phi_{ik}\cdot deg)}{64} + \frac{k_{ik}^{3}\cdot\cos(3\cdot}{45\cdot\sqrt{}}\right.$$

$$Q_{ik} = 0.281564\,\Omega$$

$$\delta R_{ik} := P_{ik}$$

$$\delta X_{ik} := Q_{ik}$$

$$Z_{Eik} := \delta R_{ik} + \delta X_{ik}\cdot i$$

$$Z_{Eik} = (0.048772 + 0.281564i)\,\Omega$$

Geometric Term

$$Z_{Gik} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{ik}}{d_{ik}}\right)\cdot 1km$$

$$Z_{Gik} = 0.068925i\,\Omega$$

Mutual Impedance for Red to White Phase

$$Z_{ik} := Z_{Gik} + Z_{Eik}$$

$$Z_{ik} = (0.048772 + 0.350489i)\,\Omega$$

Mutual Impedance Red to Blue Phase

Earth Contribution

$$k_{ij} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{ij}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{ij} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{ij}\cdot\cos\left(\phi_{ij}\cdot deg\right) + \frac{k_{ij}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{ij}}\right)\right)\cdot\cos\left(2\cdot\phi_{ij}\cdot deg\right) + \left(\phi_{ij}\cdot deg\right)\cdot\sin\left(2\cdot\right.\right.\right.$$

$$P_{ij} = 0.048762\,\Omega$$

$$Q_{ij} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{ij}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{ij}\cdot\cos\left(\phi_{ij}\cdot deg\right) - \frac{\pi\cdot k_{ij}^{2}\cdot\cos\left(2\cdot\phi_{ij}\cdot deg\right)}{64} + \frac{k_{ij}^{3}\cdot\cos\left(3\cdot\phi_{ij}\cdot d\right.}{45\cdot\sqrt{2}}\right.$$

$$Q_{ij} = 0.272035\,\Omega$$

$$\delta R_{ij} := P_{ij}$$

$$\delta X_{ij} := Q_{ij}$$

$$Z_{Eij} := \delta R_{ij} + \delta X_{ij}\cdot i$$

$$Z_{Eij} = (0.048762 + 0.272035i)\,\Omega$$

Geometric Term

$$Z_{Gij} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{ij}}{d_{ij}}\right)\cdot 1\text{km}$$

$$Z_{Gij} = 0.034943i\ \Omega$$

Mutual Impedance for Red to Blue Phase

$$Z_{ij} := Z_{Gij} + Z_{Eij}$$

$$Z_{ij} = (0.048762 + 0.306978i)\ \Omega$$

Mutual Impedance Red to Earth Wire 1

Earth Contribution

$$k_{iv} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{iv}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{iv} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{iv}\cdot\cos(\phi_{iv}\cdot deg) + \frac{k_{iv}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{iv}}\right)\right)\cdot\cos(2\cdot\phi_{iv}\cdot deg) + (\phi_{iv}\cdot deg)\cdot \text{si}\right.\right.$$

$$P_{iv} = 0.048665\ \Omega$$

$$Q_{iv} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{iv}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{iv}\cdot\cos(\phi_{iv}\cdot deg) - \frac{\pi\cdot k_{iv}^{2}\cdot\cos(2\cdot\phi_{iv}\cdot deg)}{64} + \frac{k_{iv}^{3}\cdot\cos(3\cdot}{45\cdot\sqrt{}}\right.$$

$$Q_{iv} = 0.274192\ \Omega$$

$$\delta R_{iv} := P_{iv}$$

$$\delta X_{iv} := Q_{iv}$$

$$Z_{Eiv} := \delta R_{iv} + \delta X_{iv}\cdot i$$

$$Z_{Eiv} = (0.048665 + 0.274192i)\ \Omega$$

Geometric Term

$$Z_{Giv} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{iv}}{d_{iv}}\right)\cdot 1km$$

$$Z_{Giv} = 0.116404i\,\Omega$$

Mutual Impedance for Red to Earth Wire 1

$$Z_{iv} := Z_{Giv} + Z_{Eiv}$$

$$Z_{iv} = (0.048665 + 0.390596i)\,\Omega$$

Mutual Impedance Red to Earth Wire 2

Earth Contribution

$$k_{iw} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{iw}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{iw} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{iw}\cdot\cos(\phi_{iw}\cdot deg) + \frac{k_{iw}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{iw}}\right)\right)\cdot\cos(2\cdot\phi_{iw}\cdot deg) + (\phi_{iw}\cdot deg\right.\right.$$

$$P_{iw} = 0.04866\,\Omega$$

$$Q_{iw} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{iw}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{iw}\cdot\cos(\phi_{iw}\cdot deg) - \frac{\pi\cdot k_{iw}^{2}\cdot\cos(2\cdot\phi_{iw}\cdot deg)}{64} + \frac{k_{iw}^{3}\cdot\cos}{4}\right.$$

$$Q_{iw} = 0.265712\,\Omega$$

$$\delta R_{iw} := P_{iw}$$

$$\delta X_{iw} := Q_{iw}$$

$$Z_{Eiw} := \delta R_{iw} + \delta X_{iw}\cdot i$$

$$Z_{Eiw} = (0.04866 + 0.265712i)\,\Omega$$

Geometric Term

$$Z_{Giw} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{iw}}{d_{iw}}\right)\cdot 1km$$

$$Z_{Giw} = 0.042884i\ \Omega$$

Mutual Impedance for Red to Earth Wire 2

$$Z_{iw} := Z_{Giw} + Z_{Eiw}$$

$$Z_{iw} = (0.04866 + 0.308596i)\ \Omega$$

Mutual Impedance White to Red Phase

Earth Contribution

$$k_{ki} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{ki}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{ki} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{ki}\cdot\cos\left(\phi_{ki}\cdot deg\right) + \frac{k_{ki}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{ki}}\right)\right)\cdot\cos\left(2\cdot\phi_{ki}\cdot deg\right) + \left(\phi_{ik}\cdot deg\right)\cdot si\right.\right.$$

$$P_{ki} = 0.048772\ \Omega$$

$$Q_{ki} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{ki}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{ki}\cdot\cos\left(\phi_{ki}\cdot deg\right) - \frac{\pi\cdot k_{ki}^{2}\cdot\cos\left(2\cdot\phi_{ki}\cdot deg\right)}{64} + \frac{k_{ki}^{3}\cdot\cos(3\cdot}{45\cdot\sqrt{}}\right.$$

$$Q_{ki} = 0.281564\ \Omega$$

$$\delta R_{ki} := P_{ki}$$

$$\delta X_{ki} := Q_{ki}$$

$$Z_{Eki} := \delta R_{ki} + \delta X_{ki}\cdot i$$

$$Z_{Eki} = (0.048772 + 0.281564i)\ \Omega$$

Geometric Term

$$Z_{Gki} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{ki}}{d_{ki}}\right)\cdot 1km$$

$$Z_{Gki} = 0.068925i\,\Omega$$

Mutual Impedance for White to Red Phase

$$Z_{ki} := Z_{Gki} + Z_{Eki}$$

Mutual Impedance same both ways.

$$Z_{ki} = (0.048772 + 0.350489i)\,\Omega$$

$$Z_{ik} = (0.048772 + 0.350489i)\,\Omega$$

Mutual Impedance White to Blue Phase

Earth Contribution

$$k_{kj} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{kj}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{kj} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{kj}\cdot\cos\left(\phi_{kj}\cdot deg\right) + \frac{k_{kj}^{\ 2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{kj}}\right)\right)\cdot\cos\left(2\cdot\phi_{kj}\cdot deg\right) + \left(\phi_{kj}\cdot deg\right)\cdot si\right.\right.$$

$$P_{kj} = 0.048772\,\Omega$$

$$Q_{kj} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{kj}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{kj}\cdot\cos\left(\phi_{kj}\cdot deg\right) - \frac{\pi\cdot k_{kj}^{\ 2}\cdot\cos\left(2\cdot\phi_{kj}\cdot deg\right)}{64} + \frac{k_{kj}^{\ 3}\cdot\cos(3\cdot}{45\cdot\sqrt{}}\right.$$

$$Q_{kj} = 0.281564\,\Omega$$

$$\delta R_{kj} := P_{kj}$$

$$\delta X_{kj} := Q_{kj}$$

$$Z_{Ekj} := \delta R_{kj} + \delta X_{kj}\cdot i$$

$$Z_{Ekj} = (0.048772 + 0.281564i)\,\Omega$$

Geometric Term

$$Z_{Gkj} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{kj}}{d_{kj}}\right)\cdot 1km$$

$$Z_{Gkj} = 0.068925i\,\Omega$$

Mutual Impedance for White to Blue Phase

$$Z_{kj} := Z_{Gkj} + Z_{Ekj}$$

$$Z_{kj} = (0.048772 + 0.350489i)\,\Omega$$

Mutual Impedance White to Earth Wire 1

Earth Contribution

$$k_{kv} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{kv}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{kv} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{kv}\cdot\cos\left(\phi_{kv}\cdot deg\right) + \frac{k_{kv}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{kv}}\right)\right)\cdot\cos\left(2\cdot\phi_{kv}\cdot deg\right) + \left(\phi_{kv}\cdot deg\right.\right.\right.$$

$$P_{kv} = 0.048671\,\Omega$$

$$Q_{kv} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{kv}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{kv}\cdot\cos\left(\phi_{kv}\cdot deg\right) - \frac{\pi\cdot k_{kv}^{2}\cdot\cos\left(2\cdot\phi_{kv}\cdot deg\right)}{64} + \frac{k_{kv}^{3}\cdot cos}{4}\right.$$

$$Q_{kv} = 0.272712\,\Omega$$

$$\delta R_{kv} := P_{kv}$$

$$\delta X_{kv} := Q_{kv}$$

$$Z_{Ekv} := \delta R_{kv} + \delta X_{kv}\cdot i$$

$$Z_{Ekv} = (0.048671 + 0.272712i)\,\Omega$$

Geometric Term

$$Z_{Gkv} := i \cdot \omega \cdot \left(\frac{\mu_0}{2 \cdot \pi}\right) \ln\left(\frac{D_{kv}}{d_{kv}}\right) \cdot 1km$$

$$Z_{Gkv} = 0.075473i \, \Omega$$

Mutual Impedance for White to Earth Wire 1

$$Z_{kv} := Z_{Gkv} + Z_{Ekv}$$

$$Z_{kv} = (0.048671 + 0.348185i) \, \Omega$$

Mutual Impedance White to Earth Wire 2

Earth Contribution

$$k_{kw} := 4 \cdot \pi \cdot \sqrt{5} \cdot 10^{-4} \cdot \frac{D_{kw}}{m} \cdot \sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega \cdot m}}}$$

$$P_{kw} := 4 \cdot \frac{\omega}{Hz} \cdot 10^{-4} \cdot \left[\left(\frac{\pi}{8}\right) - \frac{1}{3 \cdot \sqrt{2}} \cdot k_{kw} \cdot \cos\left(\phi_{kw} \cdot deg\right) + \frac{{k_{kw}}^2}{16} \cdot \left[\left(0.6728 + \ln\left(\frac{2}{k_{kw}}\right)\right) \cdot \cos\left(2 \cdot \phi_{kw} \cdot deg\right) + \left(\phi_{kw}\right.\right.\right.$$

$$P_{kw} = 0.048671 \, \Omega$$

$$Q_{kw} := 4 \cdot \frac{\omega}{Hz} \cdot 10^{-4} \cdot \left[-0.0386 + \left(\frac{1}{2}\right) \cdot \ln\left(\frac{2}{k_{kw}}\right) + \frac{1}{3 \cdot \sqrt{2}} \cdot k_{kw} \cdot \cos\left(\phi_{kw} \cdot deg\right) - \frac{\pi \cdot {k_{kw}}^2 \cdot \cos\left(2 \cdot \phi_{kw} \cdot deg\right)}{64} + \frac{{k_{kw}}^3}{\quad}\right.$$

$$Q_{kw} = 0.272712 \, \Omega$$

$$\delta R_{kw} := P_{kw}$$

$$\delta X_{kw} := Q_{kw}$$

$$Z_{Ekw} := \delta R_{kw} + \delta X_{kw} \cdot i$$

$$Z_{Ekw} = (0.048671 + 0.272712i) \, \Omega$$

Geometric Term

$$Z_{Gkw} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{kw}}{d_{kw}}\right)\cdot 1km$$

$$Z_{Gkw} = 0.075473i\,\Omega$$

Mutual Impedance for White to Earth Wire 2

$$Z_{kw} := Z_{Gkw} + Z_{Ekw}$$

$$Z_{kw} = (0.048671 + 0.348185i)\,\Omega$$

Mutual Impedance Blue to Red Phase

Earth Contribution

$$k_{ji} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{ji}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{ji} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{ji}\cdot\cos(\phi_{ji}\cdot deg) + \frac{k_{ji}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{ji}}\right)\right)\cdot\cos(2\cdot\phi_{ji}\cdot deg) + (\phi_{ji}\cdot deg)\cdot\sin(2\cdot\right.\right.$$

$$P_{ji} = 0.048762\,\Omega$$

$$Q_{ji} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{ji}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{ji}\cdot\cos(\phi_{ji}\cdot deg) - \frac{\pi\cdot k_{ji}^{2}\cdot\cos(2\cdot\phi_{ji}\cdot deg)}{64} + \frac{k_{ji}^{3}\cdot\cos(3\cdot\phi_{ji}\cdot d}{45\cdot\sqrt{2}}\right.$$

$$Q_{ji} = 0.272035\,\Omega$$

$$\delta R_{ji} := P_{ji}$$

$$\delta X_{ji} := Q_{ji}$$

$$Z_{Eji} := \delta R_{ji} + \delta X_{ji}\cdot i$$

$$Z_{Eji} = (0.048762 + 0.272035i)\,\Omega$$

Geometric Term

$$Z_{Gji} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{ji}}{d_{ji}}\right)\cdot 1km$$

$$Z_{Gji} = 0.034943i\ \Omega$$

Mutual Impedance for Blue to Red Phase

$$Z_{ji} := Z_{Gji} + Z_{Eji}$$

$$Z_{ji} = (0.048762 + 0.306978i)\ \Omega$$

Mutual Impedance Blue to White Phase

Earth Contribution

$$k_{jk} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{jk}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{jk} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{jk}\cdot\cos(\phi_{jk}\cdot deg) + \frac{k_{jk}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{jk}}\right)\right)\cdot\cos(2\cdot\phi_{jk}\cdot deg) + (\phi_{jk}\cdot deg)\cdot si\right.\right.$$

$$P_{jk} = 0.048772\ \Omega$$

$$Q_{jk} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{jk}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{jk}\cdot\cos(\phi_{jk}\cdot deg) - \frac{\pi\cdot k_{jk}^{2}\cdot\cos(2\cdot\phi_{jk}\cdot deg)}{64} + \frac{k_{jk}^{3}\cdot\cos(3\cdot}{45\cdot\sqrt{}}\right.$$

$$Q_{jk} = 0.281564\ \Omega$$

$$\delta R_{jk} := P_{jk}$$

$$\delta X_{jk} := Q_{jk}$$

$$Z_{Ejk} := \delta R_{jk} + \delta X_{jk}\cdot i$$

$$Z_{Ejk} = (0.048772 + 0.281564i)\ \Omega$$

Geometric Term

$$Z_{Gjk} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{jk}}{d_{jk}}\right)\cdot 1km$$

$$Z_{Gjk} = 0.068925i\,\Omega$$

Mutual Impedance for Blue to White Phase

$$Z_{jk} := Z_{Gjk} + Z_{Ejk}$$

$$Z_{jk} = (0.048772 + 0.350489i)\,\Omega$$

Mutual Impedance Blue to Earth Wire 1

Earth Contribution

$$k_{jv} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{jv}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{jv} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{jv}\cdot\cos(\phi_{jv}\cdot deg) + \frac{k_{jv}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{jv}}\right)\right)\cdot\cos(2\cdot\phi_{jv}\cdot deg) + (\phi_{jv}\cdot deg)\cdot\text{si}\right.\right.$$

$$P_{jv} = 0.04866\,\Omega$$

$$Q_{jv} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{jv}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{jv}\cdot\cos(\phi_{jv}\cdot deg) - \frac{\pi\cdot k_{jv}^{2}\cdot\cos(2\cdot\phi_{jv}\cdot deg)}{64} + \frac{k_{jv}^{3}\cdot\cos(3\cdot\text{c}}{45\cdot\sqrt{\text{:}}}\right.$$

$$Q_{jv} = 0.265712\,\Omega$$

$$\delta R_{jv} := P_{jv}$$

$$\delta X_{jv} := Q_{jv}$$

$$Z_{Ejv} := \delta R_{jv} + \delta X_{jv}\cdot i$$

$$Z_{Ejv} = (0.04866 + 0.265712i)\,\Omega$$

Geometric Term

$$Z_{Gjv} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{jv}}{d_{jv}}\right)\cdot 1km$$

$$Z_{Gjv} = 0.042884i\ \Omega$$

Mutual Impedance for Blue to Earth Wire 1

$$Z_{jv} := Z_{Gjv} + Z_{Ejv}$$

$$Z_{jv} = (0.04866 + 0.308596i)\ \Omega$$

Mutual Impedance Blue to Earth Wire 2

Earth Contribution

$$k_{jw} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{jw}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{jw} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{jw}\cdot\cos(\phi_{jw}\cdot deg) + \frac{k_{jw}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{jw}}\right)\right)\cdot\cos(2\cdot\phi_{jw}\cdot deg) + (\phi_{jw}\cdot deg\right.\right.$$

$$P_{jw} = 0.048665\ \Omega$$

$$Q_{jw} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{jw}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{jw}\cdot\cos(\phi_{jw}\cdot deg) - \frac{\pi\cdot k_{jw}^{2}\cdot\cos(2\cdot\phi_{jw}\cdot deg)}{64} + \frac{k_{jw}^{3}\cdot \cos}{4}\right.$$

$$Q_{jw} = 0.274192\ \Omega$$

$$\delta R_{jw} := P_{jw}$$

$$\delta X_{jw} := Q_{jw}$$

$$Z_{Ejw} := \delta R_{jw} + \delta X_{jw}\cdot i$$

$$Z_{Ejw} = (0.048665 + 0.274192i)\ \Omega$$

Geometric Term

$$Z_{Gjw} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{jw}}{d_{jw}}\right)\cdot 1km$$

$$Z_{Gjw} = 0.042884i\ \Omega$$

Mutual Impedance for Blue to Earth Wire 2

$$Z_{jw} := Z_{Gjw} + Z_{Ejw}$$

$$Z_{jw} = (0.048665 + 0.390596i)\ \Omega$$

Mutual Impedance Earth Wire 1 to Red Phase

Earth Contribution

$$k_{vi} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{vi}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{vi} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{vi}\cdot\cos\left(\phi_{vi}\cdot deg\right) + \frac{k_{vi}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{vi}}\right)\right)\cdot\cos\left(2\cdot\phi_{vi}\cdot deg\right) + \left(\phi_{vi}\cdot deg\right)\cdot si\right.\right.$$

$$P_{vi} = 0.048665\ \Omega$$

$$Q_{vi} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{vi}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{vi}\cdot\cos\left(\phi_{vi}\cdot deg\right) - \frac{\pi\cdot k_{vi}^{2}\cdot\cos\left(2\cdot\phi_{vi}\cdot deg\right)}{64} + \frac{k_{vi}^{3}\cdot\cos(3\cdot}{45\cdot\sqrt{}}\right.$$

$$Q_{vi} = 0.274192\ \Omega$$

$$\delta R_{vi} := P_{vi}$$

$$\delta X_{vi} := Q_{vi}$$

$$Z_{Evi} := \delta R_{vi} + \delta X_{vi}\cdot i$$

$$Z_{Evi} = (0.048665 + 0.274192i)\ \Omega$$

Geometric Term

$$Z_{Gvi} := i \cdot \omega \cdot \left(\frac{\mu_0}{2 \cdot \pi}\right) \ln\left(\frac{D_{vi}}{d_{vi}}\right) \cdot 1km$$

$$Z_{Gvi} = 0.116404i\ \Omega$$

Mutual Impedance for Earth Wire 1 to Red Phase

$$Z_{vi} := Z_{Gvi} + Z_{Evi}$$

$$Z_{vi} = (0.048665 + 0.390596i)\ \Omega$$

Mutual Impedance Earth Wire 1 to White Phase

Earth Contribution

$$k_{vk} := 4 \cdot \pi \cdot \sqrt{5} \cdot 10^{-4} \cdot \frac{D_{vk}}{m} \cdot \sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega \cdot m}}}$$

$$P_{vk} := 4 \cdot \frac{\omega}{Hz} \cdot 10^{-4} \cdot \left[\left(\frac{\pi}{8}\right) - \frac{1}{3 \cdot \sqrt{2}} \cdot k_{vk} \cdot \cos\left(\phi_{vk} \cdot deg\right) + \frac{{k_{vk}}^{2}}{16} \cdot \left[\left(0.6728 + \ln\left(\frac{2}{k_{vk}}\right)\right) \cdot \cos\left(2 \cdot \phi_{vk} \cdot deg\right) + \left(\phi_{vk} \cdot deg\right.\right.\right.$$

$$P_{vk} = 0.048671\ \Omega$$

$$Q_{vk} := 4 \cdot \frac{\omega}{Hz} \cdot 10^{-4} \cdot \left[-0.0386 + \left(\frac{1}{2}\right) \cdot \ln\left(\frac{2}{k_{vk}}\right) + \frac{1}{3 \cdot \sqrt{2}} \cdot k_{vk} \cdot \cos\left(\phi_{vk} \cdot deg\right) - \frac{\pi \cdot {k_{vk}}^{2} \cdot \cos\left(2 \cdot \phi_{vk} \cdot deg\right)}{64} + \frac{{k_{vk}}^{3} \cdot \cos}{4}\right.$$

$$Q_{vk} = 0.272712\ \Omega$$

$$\delta R_{vk} := P_{vk}$$

$$\delta X_{vk} := Q_{vk}$$

$$Z_{Evk} := \delta R_{vk} + \delta X_{vk} \cdot i$$

$$Z_{Evk} = (0.048671 + 0.272712i)\ \Omega$$

Geometric Term

$$Z_{Gvk} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{vk}}{d_{jw}}\right)\cdot 1km$$

$$Z_{Gvk} = 0.117878i\ \Omega$$

Mutual Impedance for Earth Wire 1 to White Phase

$$Z_{vk} := Z_{Gvk} + Z_{Evk}$$

$$Z_{vk} = (0.048671 + 0.39059i)\ \Omega$$

Mutual Impedance Earth Wire 1 to Blue Phase

Earth Contribution

$$k_{vj} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{vj}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{vj} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{vj}\cdot\cos\left(\phi_{vj}\cdot deg\right) + \frac{k_{vj}^{\ 2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{vj}}\right)\right)\cdot\cos\left(2\cdot\phi_{vj}\cdot deg\right) + \left(\phi_{vj}\cdot deg\right)\cdot si\right.\right.$$

$$P_{vj} = 0.04866\ \Omega$$

$$Q_{vj} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{jw}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{vj}\cdot\cos\left(\phi_{vj}\cdot deg\right) - \frac{\pi\cdot k_{vj}^{\ 2}\cdot\cos\left(2\cdot\phi_{vj}\cdot deg\right)}{64} + \frac{k_{vj}^{\ 3}\cdot\cos(3\cdot}{45\cdot\sqrt{}}\right.$$

$$Q_{vj} = 0.274193\ \Omega$$

$$\delta R_{vj} := P_{vj}$$

$$\delta X_{vj} := Q_{vj}$$

$$Z_{Evj} := \delta R_{vj} + \delta X_{vj}\cdot i$$

$$Z_{Evj} = (0.04866 + 0.274193i)\ \Omega$$

Geometric Term

$$Z_{Gvj} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{vj}}{d_{vj}}\right)\cdot 1km$$

$$Z_{Gvj} = 0.042884i\,\Omega$$

Mutual Impedance for Earth Wire 1 to Blue Phase

$$Z_{vj} := Z_{Gvj} + Z_{Evj}$$

$$Z_{vj} = (0.04866 + 0.317077i)\,\Omega$$

Mutual Impedance Earth Wire 1 to Earth Wire 2

Earth Contribution

$$k_{vw} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{vw}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{vw} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{vw}\cdot\cos\left(\phi_{vw}\cdot deg\right) + \frac{k_{vw}{}^2}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{vw}}\right)\right)\cdot\cos\left(2\cdot\phi_{vw}\cdot deg\right) + \left(\phi_{vw}\right.\right.\right.$$

$$P_{vw} = 0.04856\,\Omega$$

$$Q_{vw} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{vw}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{vw}\cdot\cos\left(\phi_{vw}\cdot deg\right) - \frac{\pi\cdot k_{vw}{}^2\cdot\cos\left(2\cdot\phi_{vw}\cdot deg\right)}{64} + \frac{k_{vw}{}^3}{}\right.$$

$$Q_{vw} = 0.259504\,\Omega$$

$$\delta R_{vw} := P_{vw}$$

$$\delta X_{vw} := Q_{vw}$$

$$Z_{Evw} := \delta R_{vw} + \delta X_{vw}\cdot i$$

$$Z_{Evw} = (0.04856 + 0.259504i)\,\Omega$$

Geometric Term

$$Z_{Gvw} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{vw}}{d_{vw}}\right)\cdot 1km$$

$$Z_{Gvw} = 0.055507i\,\Omega$$

Mutual Impedance for Earth Wire 1 to Earth Wire 2

$$Z_{vw} := Z_{Gvw} + Z_{Evw}$$

$$Z_{vw} = (0.04856 + 0.315011i)\,\Omega$$

Mutual Impedance Earth Wire 2 to Red Phase

Earth Contribution

$$k_{wi} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{wi}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{wi} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{wi}\cdot\cos(\phi_{wi}\cdot deg) + \frac{k_{wi}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{wi}}\right)\right)\cdot\cos(2\cdot\phi_{wi}\cdot deg) + (\phi_{wi}\cdot deg\right.\right.$$

$$P_{wi} = 0.04866\,\Omega$$

$$Q_{wi} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{wi}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{wi}\cdot\cos(\phi_{wi}\cdot deg) - \frac{\pi\cdot k_{wi}^{2}\cdot\cos(2\cdot\phi_{wi}\cdot deg)}{64} + \frac{k_{wi}^{3}\cdot cos}{4}\right.$$

$$Q_{wi} = 0.265712\,\Omega$$

$$\delta R_{wi} := P_{wi}$$

$$\delta X_{wi} := Q_{wi}$$

$$Z_{Ewi} := \delta R_{wi} + \delta X_{wi}\cdot i$$

$$Z_{Ewi} = (0.04866 + 0.265712i)\,\Omega$$

Geometric Term

$$Z_{Gwi} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{wi}}{d_{wi}}\right)\cdot 1km$$

$$Z_{Gwi} = 0.042884i\ \Omega$$

Mutual Impedance for Earth Wire 2 to Red

$$Z_{wi} := Z_{Gwi} + Z_{Ewi}$$

$$Z_{wi} = (0.04866 + 0.308596i)\ \Omega$$

Mutual Impedance Earth Wire 2 to White Phase

Earth Contribution

$$k_{wk} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{wk}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{wk} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{wk}\cdot\cos\left(\phi_{wk}\cdot deg\right) + \frac{k_{wk}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{wk}}\right)\right)\cdot\cos\left(2\cdot\phi_{wk}\cdot deg\right) + \left(\phi_{wk}\right.\right.\right.$$

$$P_{wk} = 0.048671\ \Omega$$

$$Q_{wk} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{wk}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{wk}\cdot\cos\left(\phi_{wk}\cdot deg\right) - \frac{\pi\cdot k_{wk}^{2}\cdot\cos\left(2\cdot\phi_{wk}\cdot deg\right)}{64} + \frac{k_{wk}^{3}}{\quad}\right.$$

$$Q_{wk} = 0.272712\ \Omega$$

$$\delta R_{wk} := P_{wk}$$

$$\delta X_{wk} := Q_{wk}$$

$$Z_{Ewk} := \delta R_{wk} + \delta X_{wk}\cdot i$$

$$Z_{Ewk} = (0.048671 + 0.272712i)\ \Omega$$

Geometric Term

$$Z_{Gwk} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{wk}}{d_{wk}}\right)\cdot 1km$$

$$Z_{Gwk} = 0.075473i\ \Omega$$

Mutual Impedance for Earth Wire 2 to White Phase

$$Z_{wk} := Z_{Gwk} + Z_{Ewk}$$

$$Z_{wk} = (0.048671 + 0.348185i)\ \Omega$$

Mutual Impedance Earth Wire 2 to Blue Phase

Earth Contribution

$$k_{wj} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{wj}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{wj} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{wj}\cdot\cos\left(\phi_{wj}\cdot deg\right) + \frac{k_{wj}^{2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{wj}}\right)\right)\cdot\cos\left(2\cdot\phi_{wj}\cdot deg\right) + \left(\phi_{wj}\cdot deg\right.\right.\right.$$

$$P_{wj} = 0.048665\ \Omega$$

$$Q_{wj} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{wj}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{wj}\cdot\cos\left(\phi_{wj}\cdot deg\right) - \frac{\pi\cdot k_{wj}^{2}\cdot\cos\left(2\cdot\phi_{wj}\cdot deg\right)}{64} + \frac{k_{wj}^{3}\cdot cos}{4}\right.$$

$$Q_{wj} = 0.274192\ \Omega$$

$$\delta R_{wj} := P_{wj}$$

$$\delta X_{wj} := Q_{wj}$$

$$Z_{Ewj} := \delta R_{wj} + \delta X_{wj}\cdot i$$

$$Z_{Ewj} = (0.048665 + 0.274192i)\ \Omega$$

Geometric Term

$$Z_{Gwj} := i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{wj}}{d_{wj}}\right)\cdot 1\text{km}$$

$$Z_{Gwj} = 0.116404i\,\Omega$$

Mutual Impedance for Earth Wire 2 to Blue Phase

$$Z_{wj} := Z_{Gwj} + Z_{Ewj}$$

$$Z_{wj} = (0.048665 + 0.390596i)\,\Omega$$

Mutual Impedance Earth Wire 2 to Earth Wire 1

Earth Contribution

$$k_{wv} := 4\cdot\pi\cdot\sqrt{5}\cdot 10^{-4}\cdot\frac{D_{wv}}{m}\cdot\sqrt{\frac{\frac{f}{Hz}}{\frac{\rho e}{\Omega\cdot m}}}$$

$$P_{wv} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[\left(\frac{\pi}{8}\right) - \frac{1}{3\cdot\sqrt{2}}\cdot k_{wv}\cdot\cos\left(\phi_{wv}\cdot deg\right) + \frac{k_{wv}^{\;2}}{16}\cdot\left[\left(0.6728 + \ln\left(\frac{2}{k_{wv}}\right)\right)\cdot\cos\left(2\cdot\phi_{wv}\cdot deg\right) + \left(\phi_{wv}\cdot\right.\right.\right.$$

$$P_{wv} = 0.04856\,\Omega$$

$$Q_{wv} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{wv}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{wv}\cdot\cos\left(\phi_{wv}\cdot deg\right) - \frac{\pi\cdot k_{wv}^{\;2}\cdot\cos\left(2\cdot\phi_{wv}\cdot deg\right)}{64} + \frac{k_{wv}^{\;3}}{\right.}$$

$$Q_{wv} = 0.259504\,\Omega$$

$$\delta R_{wv} := P_{wv}$$

$$\delta X_{wv} := Q_{wv}$$

$$Z_{Ewv} := \delta R_{wv} + \delta X_{wv}\cdot i$$

$$Z_{Ewv} = (0.04856 + 0.259504i)\,\Omega$$

Geometric Term

$$Z_{Gwv} := i \cdot \omega \cdot \left(\frac{\mu_0}{2 \cdot \pi}\right) \ln\left(\frac{D_{wv}}{d_{wv}}\right) \cdot 1km$$

$$Z_{Gwv} = 0.055507i\,\Omega$$

Mutual Impedance for Earth Wire 2 to Earth Wire 1

$$Z_{wv} := Z_{Gwv} + Z_{Ewv}$$

$$Z_{wv} = (0.04856 + 0.315011i)\,\Omega$$

Automated Calculation of Carson's Earth Correction Factors, P and Q for all Angles.

Earth Contribution

$g := 0 .. 4 \qquad h := 0 .. 4$

$\phi_{ii} := 0 \qquad \phi_{kk} := 0 \qquad \phi_{jj} := 0 \qquad \phi_{vv} := 0 \qquad \phi_{ww} := 0$

$$\phi := \begin{pmatrix} \phi_{ii} & \phi_{ik} & \phi_{ij} & \phi_{iv} & \phi_{iw} \\ \phi_{ki} & \phi_{kk} & \phi_{kj} & \phi_{kv} & \phi_{kw} \\ \phi_{ji} & \phi_{jk} & \phi_{jj} & \phi_{jv} & \phi_{jw} \\ \phi_{vi} & \phi_{vk} & \phi_{vj} & \phi_{vv} & \phi_{vw} \\ \phi_{wi} & \phi_{wk} & \phi_{wj} & \phi_{wv} & \phi_{ww} \end{pmatrix} \qquad k := \begin{pmatrix} k_{i} & k_{ik} & k_{ij} & k_{iv} & k_{iw} \\ k_{ki} & k_{k} & k_{kj} & k_{kv} & k_{kw} \\ k_{ji} & k_{jk} & k_{j} & k_{jv} & k_{jw} \\ k_{vi} & k_{vk} & k_{vj} & k_{ew} & k_{vw} \\ k_{wi} & k_{wk} & k_{wj} & k_{wv} & k_{ew} \end{pmatrix}$$

$$P_{g,h} := \left[4 \cdot \frac{\omega}{Hz} \cdot 10^{-4} \cdot \left[\left(\frac{\pi}{8}\right) - \frac{1}{3 \cdot \sqrt{2}} \cdot k_{g,h} \cdot \cos\left(\phi_{g,h} \cdot deg\right) + \frac{\left(k_{g,h}\right)^2}{16} \cdot \left[\left(0.6728 + \ln\left(\frac{2}{k_{g,h}}\right)\right) \cdot \cos\left(2 \cdot \phi_{g,h} \cdot deg\right) + \left(\right.\right.\right.\right.$$

$$P = \begin{pmatrix} 0.048767 & 0.048772 & 0.048762 & 0.048665 & 0.04866 \\ 0.048772 & 0.04878 & 0.048772 & 0.048671 & 0.048671 \\ 0.048762 & 0.048772 & 0.048767 & 0.04866 & 0.048665 \\ 0.048665 & 0.048671 & 0.04866 & 0.048564 & 0.04856 \\ 0.04866 & 0.048671 & 0.048665 & 0.04856 & 0.048564 \end{pmatrix} \Omega$$

$$Q_{g,h} := 4\cdot\frac{\omega}{Hz}\cdot 10^{-4}\cdot\left[-0.0386 + \left(\frac{1}{2}\right)\cdot\ln\left(\frac{2}{k_{g,h}}\right) + \frac{1}{3\cdot\sqrt{2}}\cdot k_{g,h}\cdot\cos\left(\phi_{g,h}\cdot deg\right) - \frac{\pi\cdot\left(k_{g,h}\right)^2\cdot\cos\left(2\cdot\phi_{g,h}\cdot deg\right)}{64} + \right.$$

$$Q = \begin{pmatrix} 0.284559 & 0.281564 & 0.272035 & 0.274192 & 0.265712 \\ 0.281564 & 0.285994 & 0.281564 & 0.272712 & 0.272712 \\ 0.272035 & 0.281564 & 0.284559 & 0.265712 & 0.274192 \\ 0.274192 & 0.272712 & 0.265712 & 0.26539 & 0.259504 \\ 0.265712 & 0.272712 & 0.274192 & 0.259504 & 0.26539 \end{pmatrix}\Omega$$

$$\delta R_{g,h} := P_{g,h}$$

$$\delta X_{g,h} := Q_{g,h}$$

$$Z_{E_{g,h}} := \delta R_{g,h} + \delta X_{g,h}\cdot i$$

$$Z_E = \begin{pmatrix} 0.04877 + 0.28456i & 0.04877 + 0.28156i & 0.04876 + 0.27203i & 0.04867 + 0.27419i & 0.04866 + 0.26571i \\ 0.04877 + 0.28156i & 0.04878 + 0.28599i & 0.04877 + 0.28156i & 0.04867 + 0.27271i & 0.04867 + 0.27271i \\ 0.04876 + 0.27203i & 0.04877 + 0.28156i & 0.04877 + 0.28456i & 0.04866 + 0.26571i & 0.04867 + 0.27419i \\ 0.04867 + 0.27419i & 0.04867 + 0.27271i & 0.04866 + 0.26571i & 0.04856 + 0.26539i & 0.04856 + 0.2595i \\ 0.04866 + 0.26571i & 0.04867 + 0.27271i & 0.04867 + 0.27419i & 0.04856 + 0.2595i & 0.04856 + 0.26539i \end{pmatrix}$$

Geometric Term

Matrix of Distances between Conductor and Image of Conductors

$D_{ii} := 2\cdot h_i$ $\quad D_{kk} := 2\cdot h_k$ $\quad D_{jj} := 2\cdot h_j$ $\quad D_{vv} := 2\cdot h_v$ $\quad D_{ww} := 2\cdot h_w$

$$D := \begin{pmatrix} D_{ii} & D_{ik} & D_{ij} & D_{iv} & D_{iw} \\ D_{ki} & D_{kk} & D_{kj} & D_{kv} & D_{kw} \\ D_{ji} & D_{jk} & D_{jj} & D_{jv} & D_{jw} \\ D_{vi} & D_{vk} & D_{vj} & D_{vv} & D_{vw} \\ D_{wi} & D_{wk} & D_{wj} & D_{wv} & D_{ww} \end{pmatrix}$$

$$D = \begin{pmatrix} 26.86 & 28.168687 & 32.785662 & 31.732405 & 36.318391 \\ 28.168687 & 26.248 & 28.168687 & 32.485544 & 32.485544 \\ 32.785662 & 28.168687 & 26.86 & 36.318391 & 31.732405 \\ 31.732405 & 32.485544 & 36.318391 & 36.566667 & 40.158201 \\ 36.318391 & 32.485544 & 31.732405 & 40.158201 & 36.566667 \end{pmatrix} \mathrm{m}$$

Matrix of Distances between Conductors

$GMR_{ew} := 533.5669 \cdot 10^{-12} \mathrm{mm}$ (See calculation for 19 strand steel conductor)

$d_{ii} := GMR_{al} \cdot \mathrm{mm}$ $d_{kk} := GMR_{al} \cdot \mathrm{mm}$ $d_{jj} := GMR_{al} \cdot \mathrm{mm}$ $d_{vv} := GMR_{ew}$ $d_{ww} := GMR_{ew}$

$$d := \begin{pmatrix} d_{ii} & d_{ik} & d_{ij} & d_{iv} & d_{iw} \\ d_{ki} & d_{kk} & d_{kj} & d_{kv} & d_{kw} \\ d_{ji} & d_{jk} & d_{jj} & d_{jv} & d_{jw} \\ d_{vi} & d_{vk} & d_{vj} & d_{vv} & d_{vw} \\ d_{wi} & d_{wk} & d_{wj} & d_{wv} & d_{ww} \end{pmatrix} \qquad d = \begin{pmatrix} 0.014369 & 9.404979 & 18.8 & 4.976429 & 18.353333 \\ 9.404979 & 0.014369 & 9.404979 & 9.772856 & 9.772856 \\ 18.8 & 9.404979 & 0.014369 & 18.353333 & 4.976429 \\ 4.976429 & 9.772856 & 18.353333 & 0 & 16.6 \\ 18.353333 & 9.772856 & 4.976429 & 16.6 & 0 \end{pmatrix} \mathrm{m}$$

Geometric Term Matrix

$$Z_G := \begin{bmatrix} i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{0,0}}{d_{0,0}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{0,1}}{d_{0,1}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{0,2}}{d_{0,2}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{0,3}}{d_{0,3}} \\ i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{1,0}}{d_{1,0}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{1,1}}{d_{1,1}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{1,2}}{d_{1,2}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{1,3}}{d_{1,3}} \\ i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{2,0}}{d_{2,0}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{2,1}}{d_{2,1}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{2,2}}{d_{2,2}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{2,3}}{d_{2,3}} \\ i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{3,0}}{d_{3,0}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{3,1}}{d_{3,1}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{3,2}}{d_{3,2}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{3,3}}{d_{3,3}} \\ i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{4,0}}{d_{4,0}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{4,1}}{d_{4,1}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{4,2}}{d_{4,2}}\right)\cdot 1\mathrm{km} & i\cdot\omega\cdot\left(\frac{\mu_0}{2\cdot\pi}\right)\ln\left(\frac{D_{4,3}}{d_{4,3}} \end{bmatrix}$$

$$Z_G = \begin{pmatrix} 0.473334i & 0.068925i & 0.034943i & 0.116404i & 0.042884i \\ 0.068925i & 0.471886i & 0.068925i & 0.075473i & 0.075473i \\ 0.034943i & 0.068925i & 0.473334i & 0.042884i & 0.116404i \\ 0.116404i & 0.075473i & 0.042884i & 2.001718i & 0.055507i \\ 0.042884i & 0.075473i & 0.116404i & 0.055507i & 2.001718i \end{pmatrix} \Omega$$

$Z_{G_{0,1}} = 0.068925i\,\Omega$

Same value, therefore calc's are correct.

$Z_{Gik} = 0.068925i\,\Omega$

Mutual Impedance Matrix

$Z_{ij} := Z_{Gij} + Z_{Eij}$

$Z_{ij} = (0.048762 + 0.306978i)\,\Omega$

$Z_M := Z_E + Z_G$

$$Z_M = \begin{pmatrix} 0.0488 + 0.7579i & 0.0488 + 0.3505i & 0.0488 + 0.307i & 0.0487 + 0.3906i & 0.0487 + 0.3086i \\ 0.0488 + 0.3505i & 0.0488 + 0.7579i & 0.0488 + 0.3505i & 0.0487 + 0.3482i & 0.0487 + 0.3482i \\ 0.0488 + 0.307i & 0.0488 + 0.3505i & 0.0488 + 0.7579i & 0.0487 + 0.3086i & 0.0487 + 0.3906i \\ 0.0487 + 0.3906i & 0.0487 + 0.3482i & 0.0487 + 0.3086i & 0.0486 + 2.2671i & 0.0486 + 0.315i \\ 0.0487 + 0.3086i & 0.0487 + 0.3482i & 0.0487 + 0.3906i & 0.0486 + 0.315i & 0.0486 + 2.2671i \end{pmatrix} \Omega$$

The diagonal values of the above matix is not used.

Overall Impedance Matrix

$$Z := \begin{pmatrix} Z_{ii} & Z_{M_{0,1}} & Z_{M_{0,2}} & Z_{M_{0,3}} & Z_{M_{0,4}} \\ Z_{M_{1,0}} & Z_{kk} & Z_{M_{1,2}} & Z_{M_{1,3}} & Z_{M_{1,4}} \\ Z_{M_{2,0}} & Z_{M_{2,1}} & Z_{jj} & Z_{M_{2,3}} & Z_{M_{2,4}} \\ Z_{M_{3,0}} & Z_{M_{3,1}} & Z_{M_{3,2}} & Z_{vv} & Z_{M_{3,4}} \\ Z_{M_{4,0}} & Z_{M_{4,1}} & Z_{M_{4,2}} & Z_{M_{4,3}} & Z_{ww} \end{pmatrix}$$

$$Z = \begin{pmatrix} 0.1 + 0.7595i & 0.0488 + 0.3505i & 0.0488 + 0.307i & 0.0487 + 0.3906i & 0.0487 + 0.3086i \\ 0.0488 + 0.3505i & 0.1 + 0.7595i & 0.0488 + 0.3505i & 0.0487 + 0.3482i & 0.0487 + 0.3482i \\ 0.0488 + 0.307i & 0.0488 + 0.3505i & 0.1 + 0.7595i & 0.0487 + 0.3086i & 0.0487 + 0.3906i \\ 0.0487 + 0.3906i & 0.0487 + 0.3482i & 0.0487 + 0.3086i & 1.9952 + 7.3256i & 0.0486 + 0.315i \\ 0.0487 + 0.3086i & 0.0487 + 0.3482i & 0.0487 + 0.3906i & 0.0486 + 0.315i & 1.9952 + 7.3256i \end{pmatrix} \Omega$$

Matrix Reduction

Reducing the above matrix to a 3 X 3 matrix, an ideal earth is assumed, ie that there is no voltage drop accross the earth conductors. The matrix is subdivided such that ZA forms a 3 X 3, whilst the rest follows the remaining conductor grouping. Using the matrix partitioning theory as shown in "Power System Analysis and Design" pg 180, we obtain;

$$\begin{pmatrix} E_P \\ 0 \end{pmatrix} := \begin{pmatrix} Z_A & Z_B \\ Z_C & Z_D \end{pmatrix} \cdot \begin{pmatrix} I_P \\ I_N \end{pmatrix}$$

$$Z_A := \begin{pmatrix} Z_{ii} & Z_{M_{0,1}} & Z_{M_{0,2}} \\ Z_{M_{1,0}} & Z_{kk} & Z_{M_{1,2}} \\ Z_{M_{2,0}} & Z_{M_{2,1}} & Z_{jj} \end{pmatrix} \qquad Z_B := \begin{pmatrix} Z_{M_{0,3}} & Z_{M_{0,4}} \\ Z_{M_{1,3}} & Z_{M_{1,4}} \\ Z_{M_{2,3}} & Z_{M_{2,3}} \end{pmatrix}$$

$$Z_C := \begin{pmatrix} Z_{M_{3,0}} & Z_{M_{3,1}} & Z_{M_{3,2}} \\ Z_{M_{4,0}} & Z_{M_{4,1}} & Z_{M_{4,2}} \end{pmatrix} \qquad Z_D := \begin{pmatrix} Z_{vv} & Z_{M_{3,4}} \\ Z_{M_{4,3}} & Z_{ww} \end{pmatrix}$$

$$Z_P := Z_A - Z_B \cdot Z_D^{-1} \cdot Z_C$$

$$Z_P = \begin{pmatrix} 0.09962 + 0.727603i & 0.048276 + 0.319113i & 0.048158 + 0.275923i \\ 0.048276 + 0.319113i & 0.099477 + 0.728284i & 0.048276 + 0.319113i \\ 0.047832 + 0.279109i & 0.047831 + 0.322731i & 0.099047 + 0.73168i \end{pmatrix} \Omega$$

Assuming a fully transposed line, the diagonal and off-diagonal elements can be averaged to obtain a symmetrical impedance matrix.

Averaged Diagonal Elements

$$Z_{aaeq} := \left(\frac{1}{3}\right)\cdot\left(Z_{P_{0,0}} + Z_{P_{1,1}} + Z_{P_{2,2}}\right)$$

$$Z_{aaeq} = (0.099382 + 0.729189i)\,\Omega$$

Averaged Off-Diagonal Elements

$$Z_{abeq} := \left(\frac{1}{3}\right)\cdot\left(Z_{P_{0,1}} + Z_{P_{0,2}} + Z_{P_{1,2}}\right)$$

$$Z_{abeq} = (0.048237 + 0.304717i)\,\Omega$$

Averaged Symmetrical Matrix

$$Z_{Pav} := \begin{pmatrix} Z_{aaeq} & Z_{abeq} & Z_{abeq} \\ Z_{abeq} & Z_{aaeq} & Z_{abeq} \\ Z_{abeq} & Z_{abeq} & Z_{aaeq} \end{pmatrix}$$

$$Z_{Pav} = \begin{pmatrix} 0.099382 + 0.729189i & 0.048237 + 0.304717i & 0.048237 + 0.304717i \\ 0.048237 + 0.304717i & 0.099382 + 0.729189i & 0.048237 + 0.304717i \\ 0.048237 + 0.304717i & 0.048237 + 0.304717i & 0.099382 + 0.729189i \end{pmatrix}\Omega$$

Symmetrical Series Sequence Impedance Matrix

$$A := \begin{pmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{pmatrix}$$

$$A^{-1} = \begin{pmatrix} 0.333333 & 0.333333 & 0.333333 \\ 0.333333 & -0.166667 + 0.288675i & -0.166667 - 0.288675i \\ 0.333333 & -0.166667 - 0.288675i & -0.166667 + 0.288675i \end{pmatrix}$$

$$Z_S := A^{-1}\cdot Z_{Pav}\cdot A$$

$$Z_S = \begin{pmatrix} 0.195855 + 1.338622i & 0 & 0 \\ 0 & 0.051145 + 0.424473i & 0 \\ 0 & 0 & 0.051145 + 0.424473i \end{pmatrix} \Omega$$

Unsymmetrical Series Impedance Matrix

$$Z_{S1} := A^{-1} \cdot Z_P \cdot A$$

$$Z_{S1} = \begin{pmatrix} 0.195598 + 1.34089i & 0.012597 - 0.007562i & -0.012467 - 0.007502i \\ -0.009295 - 0.008745i & 0.051149 + 0.423304i & -0.024932 + 0.014317i \\ 0.009751 - 0.009506i & 0.025061 + 0.01424i & 0.051398 + 0.423373i \end{pmatrix} \Omega$$

Zero Sequence Impedance

$$Z_0 := Z_{S_{0,0}}$$

$$Z_0 = (0.195855 + 1.338622i)\,\Omega$$

Check

$$Z_Z := Z_{aaeq} + 2 \cdot Z_{abeq}$$

$$Z_Z = (0.195855 + 1.338622i)\,\Omega$$

Positive Sequence Impedance

$$Z_1 := Z_{S_{1,1}}$$

$$Z_1 = (0.051145 + 0.424473i)\,\Omega$$

Check

$$Z_{pos} := Z_{aaeq} - Z_{abeq}$$

$$Z_{pos} = (0.051145 + 0.424473i)\,\Omega$$

Negative Sequence Impedance

$$Z_2 := Z_{S_{2,2}}$$

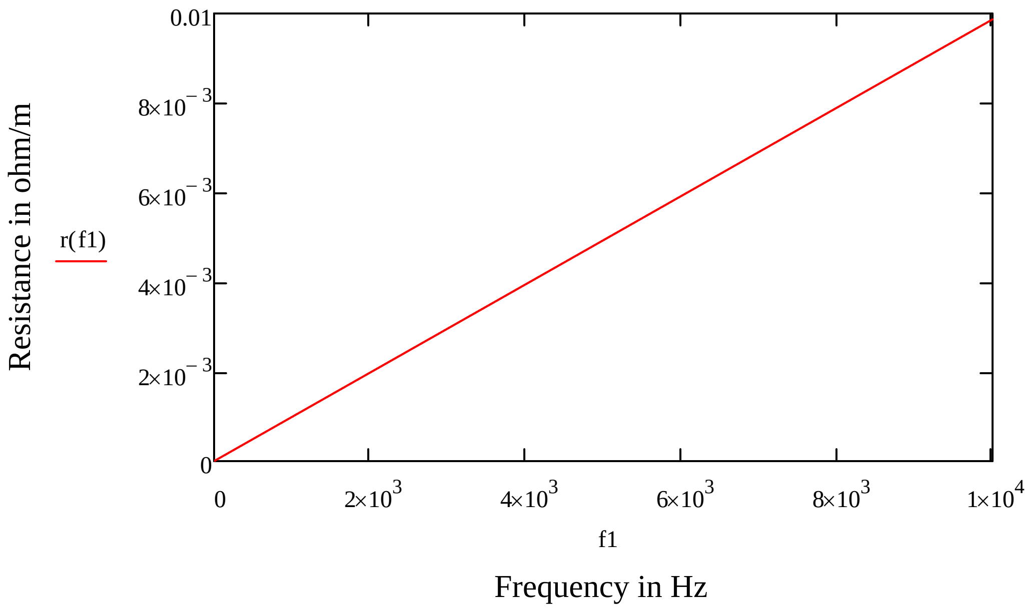
$$Z_2 = (0.051145 + 0.424473i)\,\Omega$$

Resistance of image conductor according to Power System analysis and Design - second edition is given by;

$$\rho e = 700 \frac{m^3 \cdot kg}{A^2 \cdot s^3}$$

$$f1 := 5Hz, 10Hz .. 10000Hz$$

$r(f1) := 9.869 \cdot 10^{-7} \cdot f1$

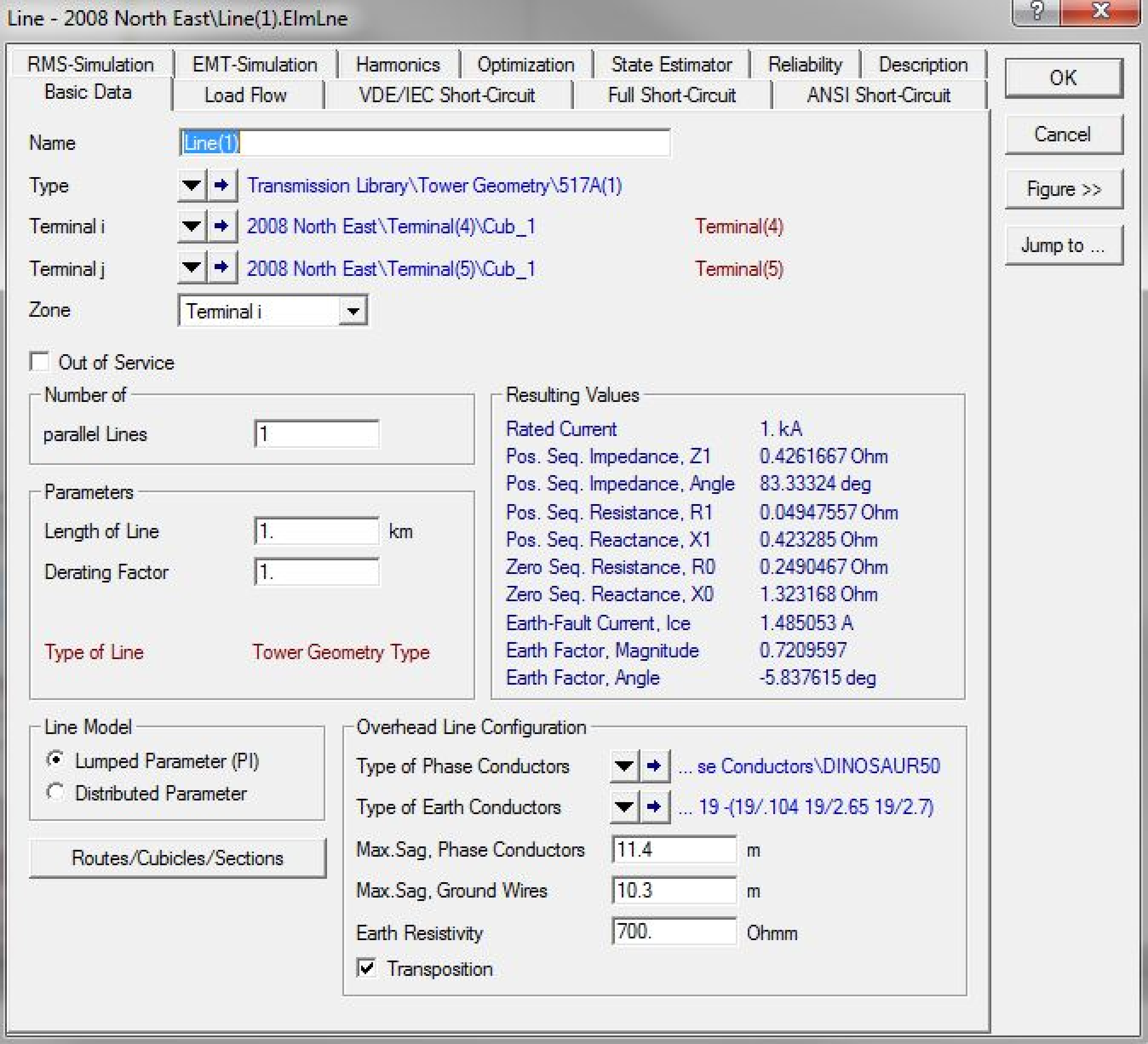


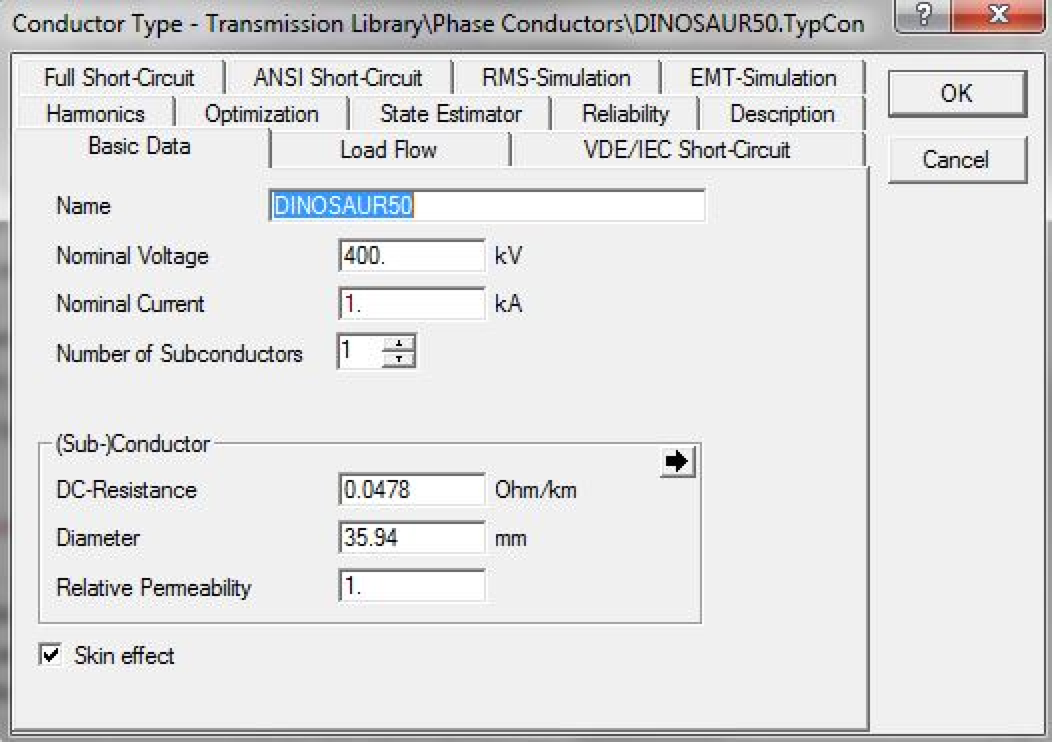
Example Results from graph at different frequencies

$r(50) \cdot 1000 = 0.049345 \quad \Omega \cdot km^{-1}$

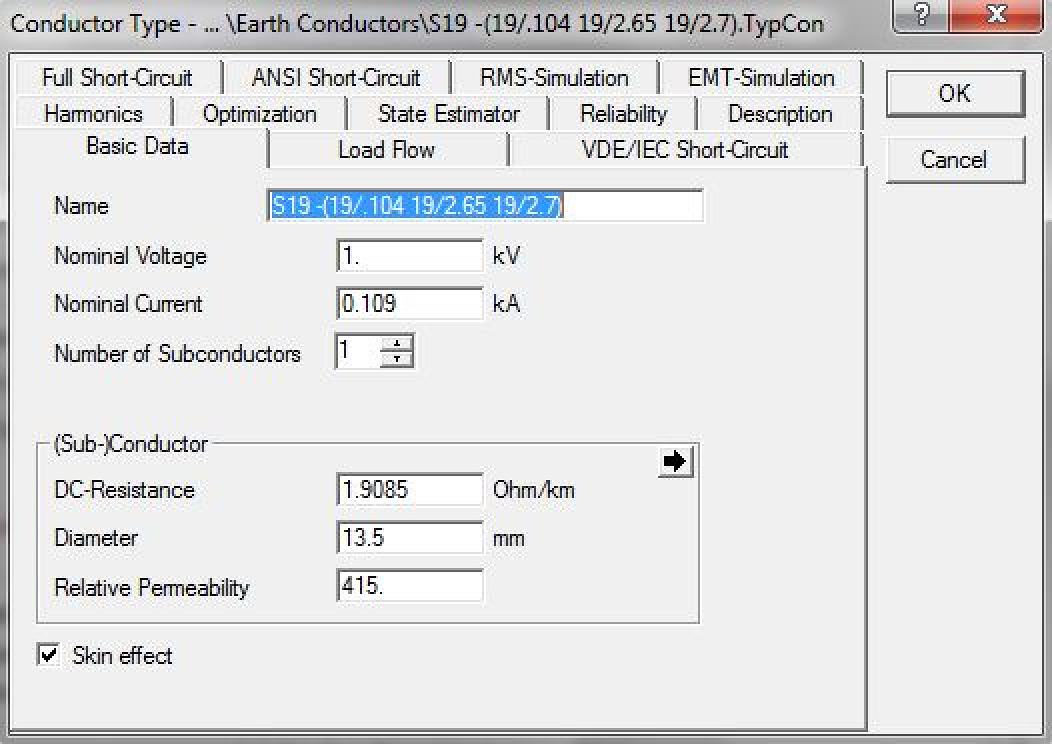
$r(500) \cdot 1000 = 0.49345 \quad \Omega \cdot km^{-1}$

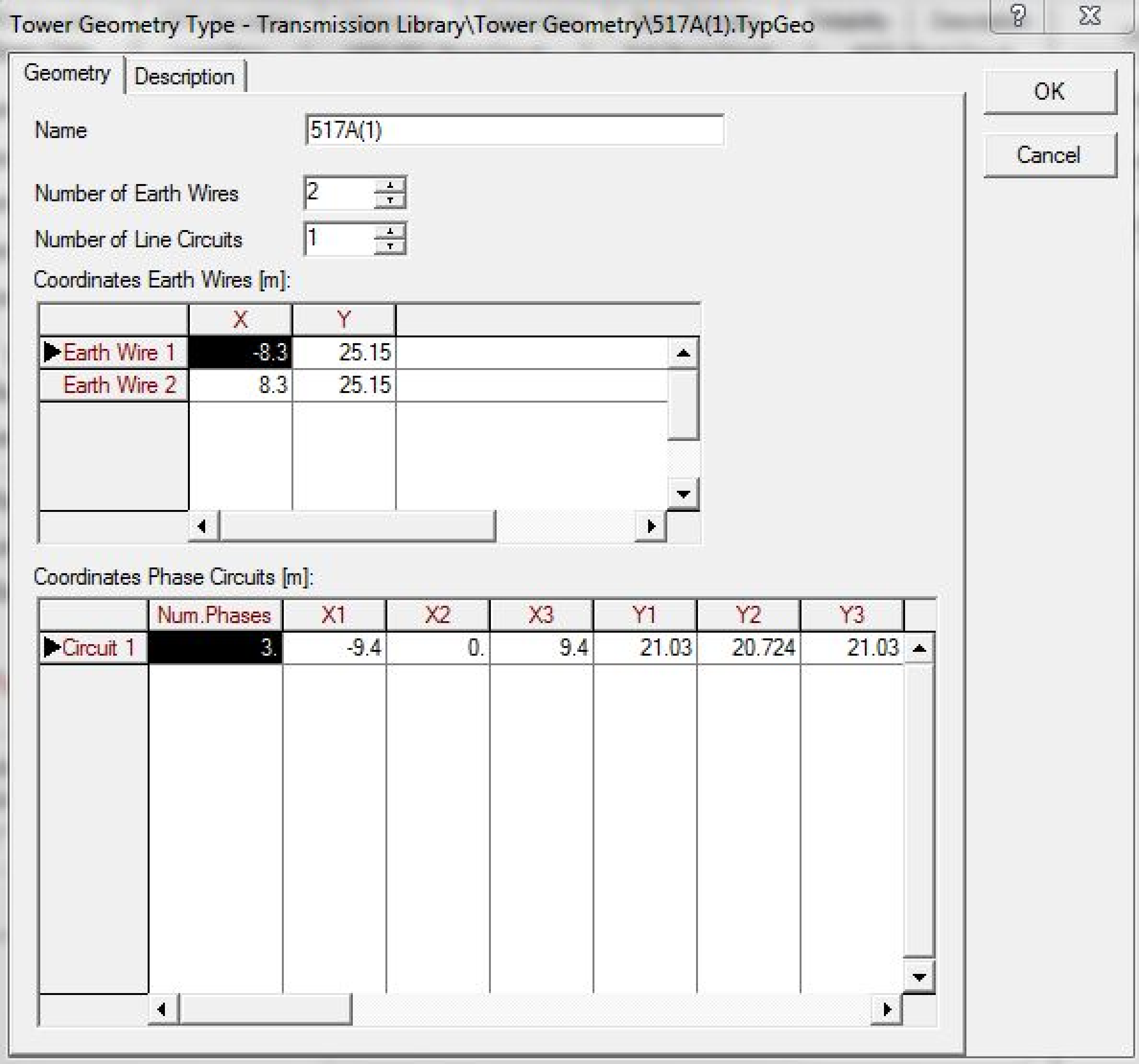
$r(2000) \cdot 1000 = 1.9738 \quad \Omega \cdot km^{-1}$


Line - 2008 North East\Line(1).ElmLne
RMS-Simulation
EMT-Simulation
Harmonics
Optimization
State Estimator
Reliability
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
Full Short-Circuit
ANSI Short-Circuit
OK
Cancel
Figure >>
Jump to ...
Name
Line(1)
Type
Transmission Library\Tower Geometry\517A(1)
Terminal i
2008 North East\Terminal(4)\Cub_1
Terminal(4)
Terminal j
2008 North East\Terminal(5)\Cub_1
Terminal(5)
Zone
Terminal i
Out of Service
Number of
parallel Lines
1
Parameters
Length of Line
1.
km
Derating Factor
1.
Type of Line
Tower Geometry Type
Resulting Values
Rated Current
1. kA
Pos. Seq. Impedance, Z1
0.4261667 Ohm
Pos. Seq. Impedance, Angle
83.33324 deg
Pos. Seq. Resistance, R1
0.04947557 Ohm
Pos. Seq. Reactance, X1
0.423285 Ohm
Zero Seq. Resistance, R0
0.2490467 Ohm
Zero Seq. Reactance, X0
1.323168 Ohm
Earth-Fault Current, Ice
1.485053 A
Earth Factor, Magnitude
0.7209597
Earth Factor, Angle
-5.837615 deg
Line Model
Lumped Parameter (PI)
Distributed Parameter
Routes/Cubicles/Sections
Overhead Line Configuration
Type of Phase Conductors
... se Conductors\DINOSAUR50
Type of Earth Conductors
... 19 -(19/.104 19/2.65 19/2.7)
Max.Sag, Phase Conductors
11.4
m
Max.Sag, Ground Wires
10.3
m
Earth Resistivity
700.
Ohmm
Transposition



Conductor Type - Transmission Library\Phase Conductors\DINOSAUR50.TypCon
Full Short-Circuit
ANSI Short-Circuit
RMS-Simulation
EMT-Simulation
Harmonics
Optimization
State Estimator
Reliability
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
OK
Cancel
Name
DINOSAUR50
Nominal Voltage
400.
kV
Nominal Current
1.
kA
Number of Subconductors
1
(Sub-)Conductor
DC-Resistance
0.0478
Ohm/km
Diameter
35.94
mm
Relative Permeability
1.
Skin effect

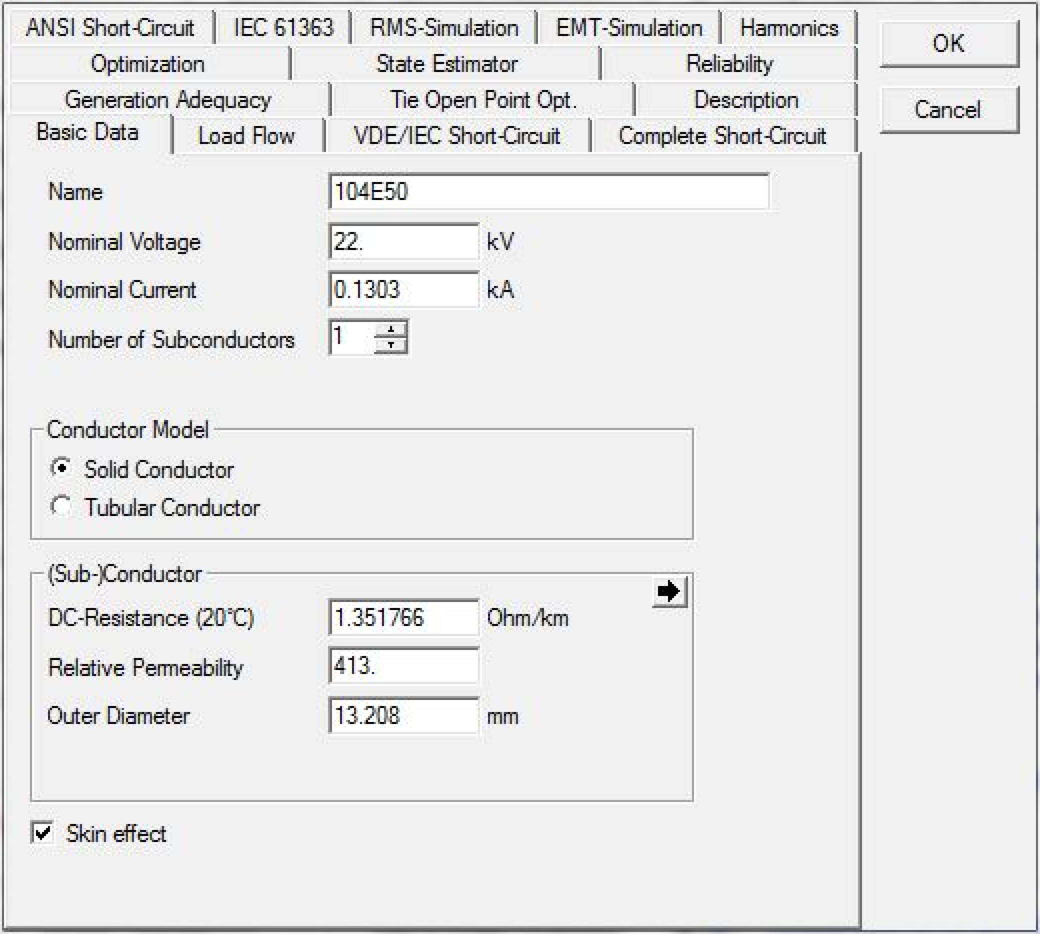

Conductor Type - ... \Earth Conductors\S19 -(19/.104 19/2.65 19/2.7).TypCon
Full Short-Circuit
ANSI Short-Circuit
RMS-Simulation
EMT-Simulation
Harmonics
Optimization
State Estimator
Reliability
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
OK
Cancel
Name
S19 -(19/.104 19/2.65 19/2.7)
Nominal Voltage
1.
kV
Nominal Current
0.109
kA
Number of Subconductors
1
(Sub-)Conductor
DC-Resistance
1.9085
Ohm/km
Diameter
13.5
mm
Relative Permeability
415.
Skin effect


Tower Geometry Type - Transmission Library\Tower Geometry\517A(1).TypGeo
Geometry
Description
OK
Cancel
Name
517A(1)
Number of Earth Wires
2
Number of Line Circuits
1
Coordinates Earth Wires [m]:
X
Y
Earth Wire 1 -8.3 25.15
Earth Wire 2 8.3 25.15
Coordinates Phase Circuits [m]:
Num.Phases
X1
X2
X3
Y1
Y2
Y3
Circuit 1 3. -9.4 0. 9.4 21.03 20.724 21.03

Appendix R

i) The following results files can be found in this appendix:

ii) Maximum PowerFactory relative permeability settable.JPG


ANSI Short-Circuit
IEC 61363
RMS-Simulation
EMT-Simulation
Harmonics
OK
Optimization
State Estimator
Reliability
Cancel
Generation Adequacy
Tie Open Point Opt.
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
Complete Short-Circuit
Name
104E50
Nominal Voltage
22.
kV
Nominal Current
0.1303
kA
Number of Subconductors
1
Conductor Model
Solid Conductor
Tubular Conductor
(Sub-)Conductor
DC-Resistance (20°C)
1.351766
Ohm/km
Relative Permeability
413.
Outer Diameter
13.208
mm
Skin effect