

Utilization of LIDAR Studies and PLS-CADD Models to Calculate Transmission Line Impedance

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Introduction

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- BS-EE from University of Rochester & ME-SE from Penn State University
- 10 years of Experience in Electrical Engineering including: Real Time Systems, Renewables, and P&C

Nathan Brazy

- Senior Software Engineer at Power Line Systems since 2012
- BS-CS and BS-CoE from Washington University in St. Louis
- Over 20 Years Experience in Software Engineering



Power Line Systems

- Founded in 1984
- Creator of the Industry Standard line design software: PLS-CADD, PLS-POLE, and TOWER
- The World-Wide Industry Standard in Overhead Line Design and Analysis Software
 - Used by over 1600 organizations
 - Used in more than 125 countries



EE 3

PLS-CADD

- PLS-CADD (Power Line Systems Computer Aided Design and Drafting)
- Integrates all aspects of line design in one platform
 - Terrain (Survey, LiDAR, Imagery, etc.)
 - Meteorological Loadings (Wind, Ice, Temperature)
 - Structure Integration (Lattice Towers, Wood, Steel, Concrete, FRP, Laminated Wood Poles)
 - Integrated (and Accurate) Conductor and Wire Sag-Tension
 - Drawings, Reports, KML, XML, SHP, etc.



PLS-CADD

- Nearly 80% of all lines 100kV and above in North America have already been modeled in PLS-CADD
 - NERC Facility Ratings Alert





PLS-CADD

 PLS-CADD was the "Digital Twin" of the Electric Grid before the term "Digital Twin" was ever dreamed of





Electrical Modeling in PLS-CADD

- 1998 Conductor Temperature (IEEE 738 and CIGRE 601)
 - Dynamic Line Rating
- 2004 Single Span EMF Calculator
- 2016 Positive Sequence Line Constants
- 2017 Rolling Sphere Lightning Protection
- 2018 Zero Sequence Line Constants
- 2019 Mutual Coupling Between Spans
 - Variable Earth Resistivity
 - 3D EMF on Multiple Spans



What is Line Impedance?

- All Transmission lines have a resistance to the flow of current
- Comprised of real and reactive components to describe the electrical characteristics of a line
- It is broken down into Symmetrical Components of 3 networks for applicability, analysis and modeling of the system:
 - Positive Sequence
 - Negative sequence
 - Zero Sequence
- The characteristics are used for transmission line modeling and overall system protection.



Transmission Line Modeling

Positive Sequence Impedance (Z₁)

- Fault Types: All fault types, typically 3-phase fault protection
- Applicability: Max load conditions; sensitivity to phase spacing

Negative Sequence Impedance (Z₂)

- Fault Types: Unbalanced loads, Phase-to-Phase and Ground Faults protection
- Applicability: System Imbalance
- Zero Sequence Impedance (Z₀)
 - Fault Types: Unbalanced loads, Ground Fault protection
 - Applicability: System Imbalance, Mutual Coupling*, sensitivity to soil resistivity



Transmission Line Protection

 Relay Setting: Positive & Zero Sequence impedance (magnitude & angle) are directly entered into relays; Negative Sequence impedance is assumed to be same as Positive Sequence

Distance Element Operations:

- Zones of Protection: **Z1**: 80%, **Z2**: ~120%, **Z3/Z4**: varies based on scheme.
- Current Compensating Factor (k₀): Relates Positive and Zero Sequence impedances used in phase to ground faults

Directional Element Operations

- Requires use of proper polarizing quantity to calculate forward or reverse thresholds for a fault
- Types of Line Protection:
 - Distance Protection
 - Directional/Non-Directional Overcurrent Protection
 - Directional comparison protection
 - Line Current Differential Protection



Uses of Line Impedance



Line Impedance Calculation: Manual Methodology

- Manual Data Inputs
 - Phase-Phase Voltage
 - Pole Tower Configuration
 - Distance between poles
 - Conductor Type
 - Static Type

- Data Outputs
 - Length (miles)
 - Positive Sequence
 - Zero Sequence
 - Capacitance

Transmission Line Number		A	Calculate		Line Cl	haracteristi	ics			BC	0.668
Phase-Phase Voltage (kV)		138	Calculate		R	0.00345	X	0.02440		DISTANCE	6.291986742
Earth Resistivity (0*m)		100	(standard value of 100)		R0	0.02057	XO	0.06849			
		Distance to									
	Pole/Tower	next Pole (in	Phase		Static 2 Type (If						Drawing
Pole/Tower Number	Configuration	feet)	Conductor Type	Static 1 Type	Applicable)	R1(%)	X1(%)	R0(%)	X0(%)	BC/j (%)	Number
Substataton Bay	62822	147.33	954 ACSR (45X7)	CC54/472	N/A	0.002	0.010	0.010	0.031	0.003	CAK-T5
286	62822	349.1	954 ACSR (45X7)	CC54/472	N/A	0.004	0.023	0.023	0.072	0.008	CAK-T5
285	62840	317.32	954 ACSR (45X7)	CC54/472	N/A	0.004	0.021	0.020	0.068	0.007	CAK-T5
284	62821	319.47	954 ACSR (45X7)	CC54/472	N/A	0.004	0.021	0.020	0.067	0.007	CAK-T5
283 62821		319.47	954 ACSR (45X7)	CC54/472	N/A	0.004	0.021	0.020	0.067	0.007	CAK-T5
282 11635-550		300.52	954 ACSR (45X7)	CC54/472	N/A	0.003	0.020	0.020	0.062	0.006	CAK-T5
004	00000	000.00	054 4000 (45)(7)	0.05 (1170)		0.004	0.004	0.004	0.075	0.000	0.01/ 7.5



Assumptions of Many Conventional Methods

- Flat Ground
- Consistent Structures
- Consistent Wire Spacing
- Average Sag Value
- Single Earth Resistivity
- Untransposed or Approximated Transposition





Advantages PLS-CADD

- Use existing line models
- Exact same models built for structural design and analysis
- Structure positions and ground elevations based on survey data
- Wire positions and phase spacing based on LiDAR data
- Accurate modeling of wire locations under different operating and weather conditions





PLS-CADD Structures and Ground

- Ground elevation data throughout right of way
- Specific structure placement for entire line
- Support for multiple lines





PLS-CADD Wires

- Every wire and every attachment modeled
- Wire position calculated for operating condition and weather
- Wires have cable properties, phase, and circuit information





Rolling Phases





How Line Constants Are Calculated

- Impedance is Resistance & Reactance
- Admittance is Conductance (0) & Susceptance
- Cable Properties are Radius, GMR, Resistance
- Distance Between Phases in a Circuit
- Distance Between Phases Between Circuits
- Distance Between Conductors and Grounds
- Height Above Ground
- Earth Resistivity



18

Intro to PLS-CADD Line Constants

- Almost all required information is already in project
- Define circuits and phases
- Set operating conditions and weather
- Select circuits and range of structures





Overview of PLS-CADD Line Constants

- Evaluates every span directly
- Measures heights and separations of wires at several points per span
- Supports bundled conductors
- Wire resistance based on cable properties and specified operating condition
- Mutual coupling between circuits on same span and adjacent spans
- Phase transpositions both at structures and within spans





PLS-CADD Line Constants Report

- Zero and Positive Sequence
 - Resistance, Reactance, and Susceptance
 - Average, Total, Per-Unit
 - Circuit Summary and Per Span
- Zero Sequence Mutual Impedance
- Span and Circuit Matrices
 - Phase and Sequence including Mutual Coupling
 - With and without ground wires
- Average wire height and positioning for every span

Line Constants Configuration	Report Options		
This report includes the zero and	positive sequence impedan	ce and susceptance totaled for circuits.	
Include summary of individua	l span results.		
Select from the options below for Whole Circuit Results	r additional matrix outputs.		
Impedance	125		
🗹 Phase	Sequence 🗹		
Complex Number	Resistance	Reactance	
Capacitance Susceptance			
Phase 🖉	Sequence 🗹		
Capacitance	Susceptance		
Average Wire Positions and Impedance with Ground Wi Potential Coefficient with Gr Capacitance	l Distances res round Wires	Impedance after Reduction Potential Coefficient after Reduction Susceptance	
Individual Circuit Per Span Res	uks.		
Impedance	Sequence		
Complex Number	Resistance	Reactance	
Capacitance_Susceptance			
Phase 🗌	Sequence		
Capacitance	Susceptance		



Line Constants Report Overview

7.02867

20.58101

0.22816

0.69310

1.62408

10.95407

4.66848 36.46401

-
•
_
Ze
Ohm)
ist (

0.11223

0.11048

0.79887

0.74413

5.38817

5.81213

0.93920

3.26479

3.58039

12.09601

Zero Sequence Mutual Impedance by Circuit Results:

Silver_Sub

Silver Sub

Green

A

	Circuit	Coupled -	Coupling		Minimum		Zero Seq	o Sequence					
	Label	with	Start	End	Cable	Avera	ge	Tota	1				
		Circuit	Structure	Structure	Length (miles)	Resistance (Ohm/mile)	Reactance (Ohm/mile)	Resistance (Ohm)	Reactance (Ohm)				
В	Red	B Green Sub	Silver Sub	10	2.0	0.34335	0.79064	0.69766	1.60652				
В	Red	A	Silver Sub	Red Sub 23	5.2	0.34676	0.71872	1.80968	3.75094				
В	Green Sub	B Red Sub	Silver Sub		2.0	0.34350	0.79036	0.69832	1.60680				
В	Zimmer	A	Silver Sub	10	2.0	0.35317	0.54667	0.69593	1.07722				
	A	B Red Sub	CAK-1580	CAK-1544	2.0	0.33295	0.45132	0.67826	0.91938				
	A	B Green Sub	CAK-1580	CAK-1547	2.0	0.35326	0.54641	0.69364	1.07291				
	A	B_Red_Sub	40CA-X33-11	CLO-5875	3.2	0.35590	0.89047	1.13114	2.83019				

10

A Blue Sub

Right click to view 'Line Constant Circuit Results' in a table, export it to XML or a database, customize table formatting. [Zero Sequence Total Reactance (Ohm)]

2.03

6.27

0.46198

0.52039

1.76115

1.92803

3.45732

3.28048

EEI 22

US CAP NUM

0.00079

0.01714

Line Constants Matrix Example

Eile Edit View Jerra	ain <u>C</u> riteria <u>Structures</u> <u>Sections</u>	ines Drafting Window Help	NE 1 4 4 4 4 4 1 1 1 1 1 1 1 1 1 1 1 1 1		A 42 46 2 40 - 6 25			- 6 :
	a c + - mit es ca d	O VICAL TR TO V	X 1+ 1- 17 10 1V V				Phase Impedance Matrix Showing V	CR ### 1</th
Search Menus, Help and Teo	chNotes 🔍 🧹							
Project View	Profile View 🚺 Plan View 🚺 30	View 🙀 Sheets View 📕 Lir	ne Constants Results					,
Span between struc Circuit Phase	tures 9 and 10 from 8.2%	to 45.4% of span length 4545 Red Bank			4545 Zimmer	Per Dis	stance	1880
Span between struc Circuit Phase 	tures 9 and 10 from 8.2%	to 45.4% of span length 4545 Red BankB	c	A	4545 ZimmerB B	Per Dis C	A A	
Span between struc Circuit Phase 	tures 9 and 10 from 8.2%	to 45.4% of span length 4545 Red BankB (Ohm/mile)	C (Ohm/mile)	A (Ohm/mile)	4545 ZimmerB (Ohm/mile)	Per Dis C (Ohm/mile)	stanceA (Ohm/mile)	
Span between struc Circuit Phase 4545 Red Bank:A	tures 9 and 10 from 8.2% 	to 45.4% of span length 	C (Ohm/mile) 0.090206 + j0.492876	A (Ohm/mile) 0.088443 + j0.542128	4545 Zinmer	-Per Dis C (Ohm/mile) 0.089997 + j0.466728	A (Ohm/mile) 0.089700 + j0.389995	
Span between struc Circuit Phase 	tures 9 and 10 from 8.2% (Ohm/mile) 0.182505 + j1.356234 0.089339 + j0.579742		C (Ohm/mile) 0.090206 + j0.492876 0.090953 + j0.564596	A (Ohm/mile) 0.088443 + j0.542128 0.089143 + j0.500074	4545 Zimmer	-Per Dis C (Ohm/mile) 0.089997 + j0.466728 0.090729 + j0.469363	A (Ohm/mile) 0.089700 + j0.389995 0.090408 + j0.384483	
Span between struc Circuit Phase 1 4545 Red Bank:A 4545 Red Bank:B 4545 Red Bank:C	Lures 9 and 10 from 8.2% (Ohm/mile) p.182505 + j1.356234 0.089339 + j0.575742 0.089376 + j0.452911	to 45.4% of span length 	C (Ohm/mile) 0.090206 + j0.492876 0.090953 + j0.564556 0.185712 + j1.352534	A (Ohm/mile) 0.089443 + j0.542128 0.089143 + j0.560074 0.089914 + j0.469869	-4545 Zimmer- B (Ohm/mile) 0.089109 + j0.496032 0.089621 + j0.493757 0.090677 + j0.494283	Per Dis C (Ohm/mile) 0.089997 + j0.466728 0.090729 + j0.489363 0.09169 + j0.530978	A (Ohm/mile) 0.085700 + j0.385955 0.090408 + j0.310666 0.091284 + j0.410666	(Ohm/mile) (Ohm/mile) 0.099673 + j0.39815; 0.099588 + j0.404981 0.991668 + j0.42466(
Span between struc Circuit Phase 	Lures 9 and 10 from 8.24 (Ohm/mile) p.182505 + j1.356234 0.099339 + j0.575742 0.099339 + j0.452911 0.088633 + j0.541903	to 45.4% of span length 	C (Ohm/mile) 0.090206 + j0.492876 0.090953 + j0.564596 0.185712 + j1.352534 0.090210 + j0.456666	A (Otm/mile) 0.088443 + j0.542128 0.089143 + j0.500074 0.089981 + j0.469865 0.182356 + j1.356408	-4545 Zimmer- B (Ohm/mile) 0.089109 + j0.496032 0.089621 + j0.49423757 0.090677 + j0.494283 0.089154 + j0.570662	-Per Dis C (Otm/mile) 0.089897 + j0.466728 0.090729 + j0.489363 0.090037 + j0.530978 0.090037 + j0.491001	Lance	I (Ohm/mile) 0.089873 + j0.39815 0.090588 + j0.404981 0.091468 + j0.42466 0.89950 + j0.42701
Span between struc Circuit Phase 	tures 9 and 10 from 8.2% 	to 45.4% of span length 	C (Otau/mile) 0.090206 + j0.452876 0.090553 + j0.564596 0.185712 + j1.352534 0.090210 + j0.459606 0.091016 + j0.453899	A (Ohm/mile) 0.088443 + j0.542128 0.089143 + j0.50074 0.089984 + j0.469869 0.182358 + j1.356408 0.082254 + j0.570543		-Per Dia c (Ohm/m1le) 0.089997 + j0.466728 0.091609 + j0.53097 0.090037 + j0.49303 0.090037 + j0.491001 0.090849 + j0.566727	A (Ohm/m11e) 0.089700 + 30.389995 0.090408 + 30.394483 0.09128 + 30.410666 0.089798 + 30.410666 0.089798 + 30.4156561	
Span between struc Circuit Phase 1 4545 Red Bank:A 4545 Red Bank:C 4545 Red Bank:C 4545 Zimmer:B 4545 Zimmer:B	bures 9 and 10 from 8.2% (Ohm/mile) p.182505 + j1.356234 0.099339 + j0.579742 0.090376 + j0.452911 0.080633 + j0.45291 0.080403 + j0.45261 0.090208 + j0.466485	to 45.4% of span length 4545 Red Bank (Ohm/mile) 0.089321 + 30.559764 0.183922 + 31.354555 0.090904 + 30.458270 0.089319 + 30.458270 0.099013 + 30.4593432 0.090926 + 30.4593432	C (Ohm/mile) 0.090206 + j0.492376 0.090953 + j0.564596 0.085712 + j0.45620 0.090210 + j0.45600 0.090210 + j0.45600 0.091016 + j0.393899 0.091863 + j0.530697	A (Obm/mile) 0.089443 + 30.542120 0.089143 + 30.50074 0.089981 + 30.458659 0.089254 + 31.35640 0.089254 + 30.570543 0.080045 + 30.45055	4545 Zimmer B (Ohn/mile) 0.089109 + 30.496032 0.089621 + 30.4967357 0.089647 + 30.493757 0.089154 + 30.57062 0.183825 + 31.354677 0.090754 + 30.569832	Per Di C (0hm/nile) 0.089897 + J0.466726 0.090729 + J0.489363 0.091609 + J0.489363 0.090017 + J0.48030 0.090031 + J0.481001 0.090045 + J0.481001 0.089564 + J1.38269727	A (Ohm/mile) 0.089700 + 30.389595 0.090408 + 30.394483 0.081284 + 30.410666 0.089796 + 30.415066 0.089596 + 30.45561 0.095146 + 30.45561	
Span between struc Circuit Phame 1 4545 Red Bank:A 4545 Red Bank:C 4545 Zammer:A 4545 Zimmer:C 1890:A	tures 9 and 10 from 8.2% (char, 16, 10, 12, 12, 12, 12, 12, 12, 12, 12, 12, 12	to 45.4% of span length 	C (Otau/mile) 0.090206 + j0.492876 0.090953 + j0.564596 0.185712 + j1.35234 0.090210 + j0.459606 0.091016 + j0.453099 0.091863 + j0.300697 0.092349 - j0.409476	(Otm/mile) 0.088443 + 30.542128 0.089143 + 30.500074 0.089581 + 30.45065 0.182358 + 31.356408 0.082534 + 30.450687 0.090054 + 30.418087	4545 Zimmer B (Ohm/mli2) 0.089109 + 30.456032 0.089621 + 30.4593757 0.090677 + 30.454233 0.089154 + 30.570662 0.183825 + 31.354677 0.090756 + 30.558932 0.091316 + 30.453764	Per Dis C (Otm/mil20) 0.089997 + j0.466728 0.090728 + j0.489343 0.091094 - j0.530978 0.090037 + j0.530978 0.090048 + j0.565727 0.185563 + j1.352697 0.092242 + j0.46263	Atance (Otam/mile) 0.089700 + 30.389995 0.090408 + 30.394483 0.09124 + 30.41060 0.095795 + 30.419605 0.090616 + 30.4565172 0.020529 + 31.561372	1880-1 (Ohm/mil0) 0.099873 + j0.39815 0.095588 + j0.404981 0.091684 + j0.42460 0.095960 + j0.42701' 0.095781 + j0.46747' 0.095260 + j0.486681 0.052260 + j0.667061
Span between struc Circuit Phase 4545 Red Bank:A 4545 Red Bank:B 4545 Red Bank:C 4545 Zinmer:B 4545 Zinmer:C 1880:B	bit 10 from 8.2% (Ohm/mile) (Ohm/mile) b.182505 + j1.356234 0.099399 + j0.579742 0.099395 + j0.579742 0.090376 + j0.452911 0.089403 + j0.45291 0.090208 + j0.452915 0.090208 + j0.452615 0.090208 + j0.456685 0.090208 + j0.456685 0.090681 + j0.388855 0.090617 + j0.3897111 0.38911	to 45.4% of span length 	C (Othe/mile) 0.090206 + j0.492276 0.090953 + j0.564596 0.05712 + j1.352534 0.090210 + j0.45606 0.091016 + j0.45806 0.091016 + j0.30897 0.092343 + j0.409476 0.092434 - j0.423570	A (Ohm/mile) 0.089443 + 30.542126 0.089143 + 30.50074 0.089801 + 30.458669 0.082554 + 30.570543 0.080054 + 30.438657 0.080684 + 30.418658	4545 Zimmer B (Ohn/Mile) 0.089109 + 30.496032 0.089621 + 30.493757 0.089627 + 30.493757 0.089154 + 30.57642 0.183825 + 31.354677 0.090756 + 30.569832 0.091316 + 30.5593764 0.09136 + 30.46677	Per Di C (0hs/nile) 0.089997 + j0.466726 0.090729 + j0.489363 0.091609 + j0.530978 0.090409 + j0.45001 0.089049 + j0.45001 0.185564 + j1.35267 0.092242 + j0.456727	A (Ohm/mile) 0.089700 + 30.385955 0.080408 + 30.35483 0.09128 + 30.410666 0.089799 + 30.415066 0.089799 + 30.415069 0.090616 + 30.45561 0.09142 + 30.45151 0.09124 + 30.45151 0.02526 + 30.45151	1880

Circuit	Per Distance	Per Distance	Per Distance	Per Distance	Per Distance	Per Distance	Span Total	Span Total	Span Total						
Phase	4545 Ked Bank	4545 Red Bank	4545 Red Bank	4545 Zimmer	4545 Zimmer	4545 Zimmer	1880	1880	1880	Shield	Shield	Shield	4545 Red Bank	4545 Ked Bank	4545 Red Bank
	A .	в	C	A	в	c	A	в	c	SW	SW	SW	A	в	L.
	(Ohm/mile)	(Ohm/mile)	(Ohm/mile)	(Ohm/mile)	(Ohm/mile)	(Ohm/mile)	(Ohm)	(Ohm)	(Ohm)						
1 4545 Red Bank:A	0.182505 + j1.35623	0.089321 + 30.579764	0.090206 + 10.49287	0.088443 + j0.542120	0.089109 + 10.49603;	0.089997 + 30.466728	0.089700 + 10.389999!	0.089873 + j0.39815;	0.089949 + 10.384740	0.087528 + 10.539623	0.087528 + 10.510551	0.089370 + 10.401903	0.013749 + j0.102173	0.006729 + 10.04367	0.006796 + 10.037
2 4545 Red Bank:B	0.089339 + 30.57974:	0.183929 + 11.354551	0.090953 + 30.56459	0.059143 + 30.500074	0.089821 + 50.49375	0.090729 + j0.48936:	0.090408 + 50.39448:	0.090588 + 30.404988	0.090661 + 30.390458	0.088217 + 30.474458	0.088211 + j0.459211	0.090073 + 30.404681	0.006730 + 50.043674	0.013856 + j0.10204!	0.006852 + j0.042
3 4545 Red Bank:C	0.090176 + j0.49291	0.090904 + 10.56465:	0.185712 + j1.35253+	0.089981 + j0.469869	0.090677 + 10.49428:	0.091609 + j0.530970	0.091284 + j0.410664	0.091468 + 30.424660	0.091544 + 10.40802:	0.089026 + j0.42983;	0.089025 + 10.42647	0.090940 + 10.419031	0.006793 + 10.03713:	0.006848 + j0.042531	0.013990 + j0.101
4 4545 Zimmer:A	0.088633 + 10.54190:	0.089319 + 10.499870	0.090210 + 30.46960	0.182358 + j1.356400	0.089154 + 10.57066;	0.090037 + 30.49100;	0.089798 + 10.419601	0.089960 + 10.42701	0.090048 + 10.411465	0.087537 + 10.503674	0.087561 + 10.551975	0.089462 + 10.436987	0.006677 + 30.040824	0.006729 + 10.03765	0.006796 + 10.035
5 4545 Zimmer:B	0.089403 + 10.49568	0.090103 + 10.49343:	0.091016 + 30.493891	0.089254 + j0.57054:	0.183825 + 31.35467"	0.090849 + 30.56972"	0.090616 + 30.45456:	0.090781 + 30.467474	0.090872 + 10.445104	0.088284 + 30.450705	0.088315 + 10.47744	0.090271 + 30.476019	0.006735 + 30.03734:	0.006788 + 30.03717;	0.006857 + 30.037
6 4545 Zimmer:C	0.090208 + j0.46648!	0.090926 + 30.48914:	0.091863 + j0.53069	0.090049 + 30.49098	0.090756 + j0.56983;	0.185563 + j1.35269	0.091428 + j0.46517;	0.091600 + 10.486680	0.091691 + j0.45955;	0.089062 + j0.42027	0.089088 + j0.43345;	0.091076 + 30.479878	0.006796 + j0.03514:	0.006850 + j0.036841	0.006920 + 10.039
7 1080:A	0.090681 + j0.388855	0.091389 + j0.393351	0.092343 + 30.409474	0.090584 + j0.418698	0.091316 + j0.45376	0.092242 + j0.46426:	0.202992 + j1.36133)	0.092260 + j0.667061	0.092377 + j0.713424	0.089532 + j0.36981'	0.089607 + j0.38874	0.091737 + j0.655769	0.006831 + j0.02929*	0.006885 + j0.02963:	0.006957 + 10.030
8 1000:B	0.090774 + j0.397113	0.091487 + j0.40396;	0.092445 + 10.423570	0.090664 + j0.426201	0.091396 + 10.466771	0.092328 + j0.48587;	0.092168 + j0.66716!	0.203211 + j1.361090	0.092438 + j0.654065	0.089618 + j0.37488'	0.089684 + j0.39281	0.091799 + j0.631885	0.006838 + j0.029914	0.006892 + j0.03043;	0.006964 + j0.031
9 1880:C	0.090936 + j0.383591	0.091649 + j0.389333	0.092611 + j0.40682!	0.090840 + j0.41055:	0.091577 + 30.44430	0.092511 + 10.458643	0.092376 + 30.713424	0.092531 + j0.653964	0.203533 + j1.36073*	0.089779 + 10.364304	0.089855 + j0.38165'	0.092003 + 10.598667	0.006851 + j0.028890	0.006904 + j0.02933(0.006977 + 10.030
10 Shield:SW	0.087579 + 10.539555	0.088251 + 10.47441	0.089109 + j0.429731	0.087405 + j0.50383'	0.088053 + 10.450988	0.088912 + j0.42045:	0.088637 + 30.37088:	0.088801 + j0.37585.	0.088878 + j0.36537:	1.105613 + j1.479890	0.086517 + 30.56493;	0.088316 + j0.382306	0.006598 + j0.04064	0.006648 + 30.035740	0.006713 + j0.032
11 Shield:SW	0.087687 + 10.510364	0.088355 + j0.459048	0.089220 + j0.426248	0.087536 + j0.552005	0.088192 + j0.47758!	0.089050 + 30.43349"	0.088818 + 30.389680	0.088975 + j0.393650	0.089061 + 30.38259:	0.086620 + j0.56480:	1.105742 + 31.479721	0.088491 + j0.403790	0.006606 + 30.038448	0.006656 + j0.03458:	0.006721 + j0.032
12 Shield:SW	0.090304 + j0.40081;	0.091006 + 10.40360+	0.091950 + 10.417881	0.090202 + j0.43612:	0.090925 + 10.47526!	0.091841 + j0.479014	0.091697 + j0.65581:	0.091850 + j0.631828	0.091963 + 10.598713	0.089166 + j0.38128'	0.089236 + j0.402902	1.110433 + j1.474170	0.006803 + j0.030195	0.006856 + j0.03040!	0.006927 + j0.031
C															>

Done

0.006928 + j0.045103 0.006717 + j0.028724 0.006723 + j0.030352 0.083654 + j0.111055

Right click to view the results in a table, export them to XML or a database, or customize table formatting including showing or hiding columns.

Shield:SW

US CAP NUM

Mutual Coupling

- Magnetic Mutual Induction in multiple-circuit or parallel single-circuit Transmission Lines that share the same Right of Way/Towers
- The magnetic field of one circuit will induce a voltage on the other circuit.

How does it affect Line Modeling?

- Affects Zero Sequence Network
 - In parallel lines, Zero Sequence Current flowing induces a Zero Sequence Voltage on neighboring line
 - Causes ground distance elements of relays to under or over-reach
- Coordination of Zones of Protection
- Fault Location



Real World Example with Mutual Coupling

- 138kV Circuit A values were obtained from Excel Calculations
- As a comparison, PLS-CADD Line Constants Calculations were performed to assess the accuracy of the model.
- 138kV Circuit A Values From both Excel & PLS-CADD are shown.

	Excel	PLS-CADD	% Difference
LENGTH	6.3	6.28	0.32%
R1 (%)	0.35	0.36	3.85%
X1 (%)	2.45	2.453	0.12%
R0 (%)	1.95	1.831	6.5%
X0 (%)	6.59	6.879	4.20%

Next we introduce 345 kV Circuit B into the model



Real World Example with Mutual Coupling

- 138 kV Circuit A 6 miles (Purple)
- 345 kV Circuit B is 19 miles (Red)
- Share the same right of way for 2 miles
- Share the same towers for 3.2 miles.
- Mutually Coupled for 5.2 miles



PLS-CADD Model with 138kV Circuit A and 345kV Circuit B



Real World Example with Mutual Coupling

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A	ll spans using de	fault earth re	sistivity spec	ifed above.														
7.4	ine Constant Circ	nit Regulte.																
	Circuit		-Circuit		- Minimum		-Zero Sequen	ce	Pos	itive Sequer	nce	Z	ero Sequence		Posi	tive Sequen	ce	Ze
	Paper	st	ructure	Structur	e Length	Resistanc	e Reactanc	e Susceptance	Resistance	Reactance	Susceptance	Resistance	Reactance	Susceptance	Resistance	Reactance	Susceptance	Resistance
					(miles)	(Ohm/mile) (Ohm/mile) (uMho/mile)	(Ohm/mile)	(Ohm/mile)	(uMho/mile)	(Ohm)	(Ohm)	(uMho)	(Ohm)	(Ohm)	(uMho)	(Ohm)
	B Ded	Silver	Sub	Red Sub	19 08	0 4821	2 2 0115	2 3 18150	0 10803	0 80060	5 30030	0 10027	38 38361	60 71110	2 06136	15 45056	101 31373	0.00773
E	B Green	Silver	Sub	10	2.03	0.4619	8 1.7611	5 3.45732	0.11223	0.79887	5.38817	0.93920	3.58039	7.02867	0.22816	1.62408	10.95407	0.00079
	A	Silver	Sub	A_Blue_Sub	6.27	0.5203	9 1.9280	3 3.28048	0.11048	0.74413	5.81213	3.26479	12.09601	20.58101	0.69310	4.66848	36.46401	0.01714
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Ze	ero Sequence Mutu	al Impedance b	y Circuit Resu	ilts:														
	Circuit	Coupled and	Coupling	M	inimum I _		Taxa Cam											
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		Circuit	Structure	Structure	Length	Resistance	Reactance	Resistance 1	Reactance					B				
				(miles)	(Ohm/mile)	(Ohm/mile)	(Ohm)	(Ohm)									
E	B Red	B Green Sub	Silver Sub	10	2.0	0.34335	0.79064	0.69766	1.60652									
E	B Red	A _	Silver_Sub	Red_Sub_23	5.2	0.34676	0.71872	1.80968	3.75094			P	\					
	B Green_Sub	B Red_Sub	Silver_Sub	10	2.0	0.34350	0.79036	0.69832	1.60680									
	B Zimmer	A	Silver_Sub	10	2.0	0.35317	0.54667	0.69593	1.07722									
	A	B_Red_Sub	CAK-1580	CAK-1544	2.0	0.33295	0.45132	0.67826	0.91938								1	
	A	B_Green_Sub	CAK-1580	CAK-1547	2.0	0.35326	0.54641	0.69364	1.07291								1	
	A	B_Red_Sub	40CA-X33-11	CLO-5875	3.2	0.35590	0.89047	1.13114	2.83019				_				1	
R	ight click to view 'Lir	ne Constant Circui	it Results' in a tal	ble, export it to	XML or a d	atabase, custor	nize table form	natting. [Zero Se	quence Total Rea	ctance (Ohm)]								US CAP NUM

EE 27

Operating Conditions

- Wire temperature directly affects resistance
- Increased Sag has small affect on a circuit's Zero Reactance
- More noticeable with multiple circuits
 - Different distances between phases of adjacent circuits
 - Zero Sequence Susceptance and Mutual Impedance affected



Variable Earth Resistivity

- Significantly affects the Zero Sequence Impedance
- Varies dramatically based on ground conditions
 - From 10 to 10,000 Ohm*m
- One Example: Changing resistivity from 100 to 10
 - Zero Sequence Resistance changed by ~25%
 - Zero Sequence Reactance changed by ~15%
- Single line could cover urban, wetlands, and farmlands
- PLS-CADD supports different Earth Resistivity per span



PLS-CADD Lightning Protection

- Rolling Sphere Method (IEEE 998)
- Actual Wire Positions Based on Weather Case
- Surveyed Ground Elevations





PLS-CADD 3D EMF

- Many of the same benefits as Line Constants
- Calculates both Electric and Magnetic Fields
- Analyze entire project at once
- Accounts for adjacent and crossing lines





3D EMF on Surveyed Ground



Power Line Systems

- Web: <u>www.powerlinesystems.com</u>
- Email: info@powerlinesystems.com
- Technical Note on the Full Line Constants Feature





The Edison Electric Institute (EEI) is the association that represents all U.S. investor-owned electric companies. Our members provide electricity for about 220 million Americans, and operate in all 50 states and the District of Columbia. As a whole, the electric power industry supports more than 7 million jobs in communities across the United States.

In addition to our U.S. members, EEI has more than 60 international electric companies, with operations in more than 90 countries, as International Members, and hundreds of industry suppliers and related organizations as Associate Members.

Organized in 1933, EEI provides public policy leadership, strategic business intelligence, and essential conferences and forums.

For more information, visit our Web site at www.eei.org.



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