Edison Electric INSTITUTE

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

Transmission, Distribution, Metering & Mutual Assistance Conference
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Minneapolis, Minnesota

Introduction

- Maria Rodriguez, E.I.T.
  - Protection & Controls Engineer at Duke Energy Ohio since March 2019
  - 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

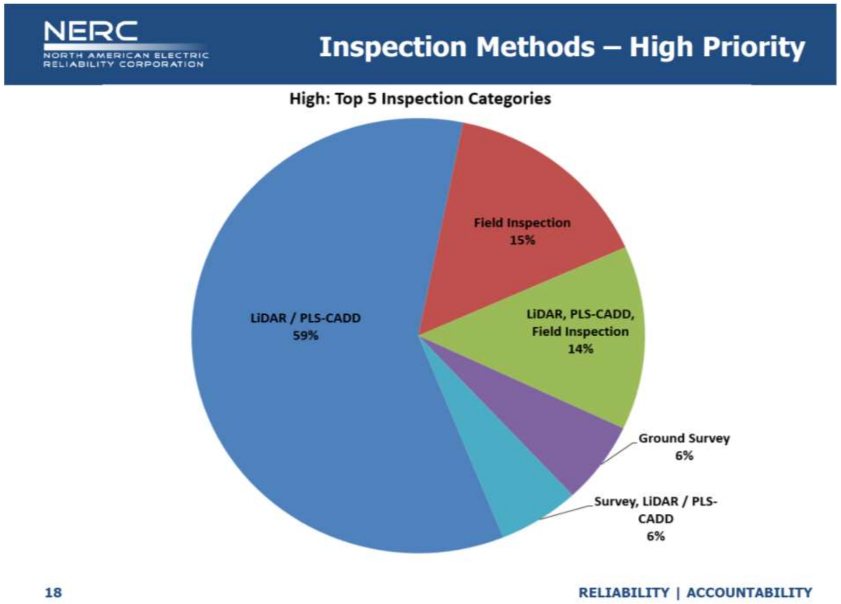
POWER LINE® SYSTEMS

PLS-CADD

- **PLS-CADD** (**P**ower **L**ine **S**ystems –
  Computer **A**ided **D**esign and **D**rafting)
- 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.

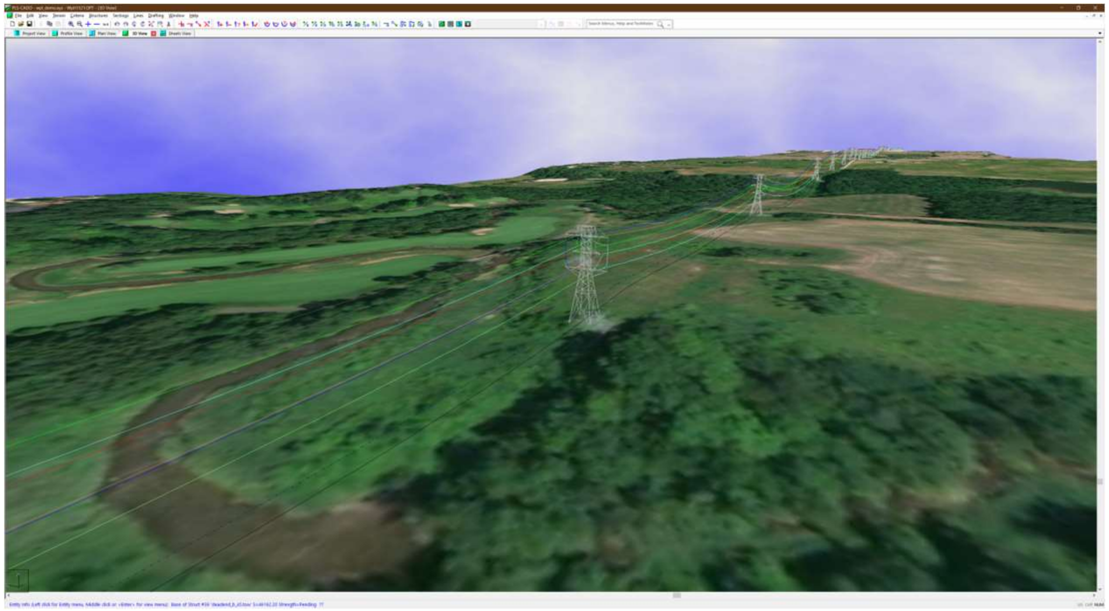
PLS-CADD

- 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 (Z_1)**
  - Fault Types: All fault types, typically 3-phase fault protection
  - Applicability: Max load conditions; sensitivity to phase spacing

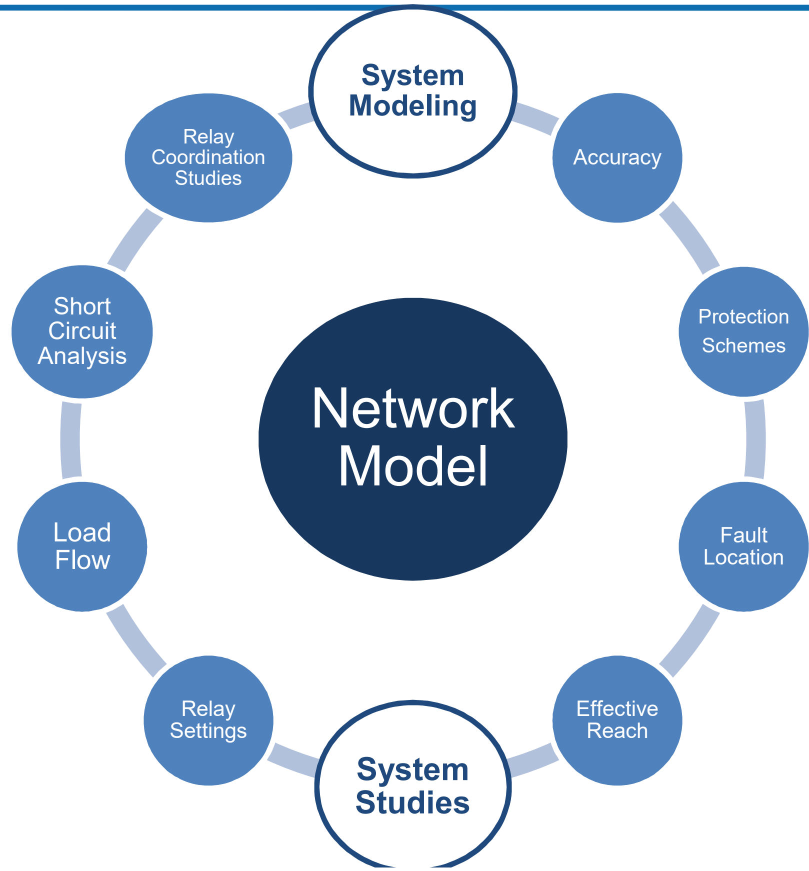
- **Negative Sequence Impedance (Z_2)**
  - Fault Types: Unbalanced loads, Phase-to-Phase and Ground Faults protection
  - Applicability: System Imbalance

- **Zero Sequence Impedance (Z_0)**
  - 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 **(k_0):** 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

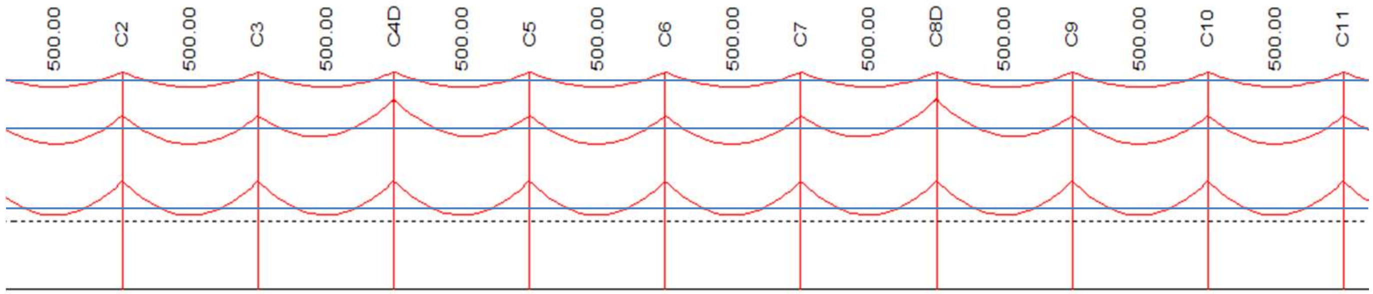
- Manual Data Inputs
  - Phase-Phase Voltage
  - Pole Tower Configuration
  - Distance between poles
  - Conductor Type
  - Static Type
- Data Outputs
  - Length (miles)
  - Positive Sequence
  - Zero Sequence
  - Capacitance

Transmission Line Number	A	Calculate	Line Characteristics					BC	0.668
Phase-Phase Voltage (kV)	138		R	0.00345	X	0.02440		DISTANCE	6.291986742
Earth Resistivity (Ω*m)	100	(standard value of 100)	R0	0.02057	X0	0.06849			

Pole/Tower Number	Pole/Tower Configuration	Distance to next Pole (in feet)	Phase Conductor Type	Static 1 Type	Static 2 Type (If Applicable)	R1(%)	X1(%)	R0(%)	X0(%)	BC/j (%)	Drawing 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

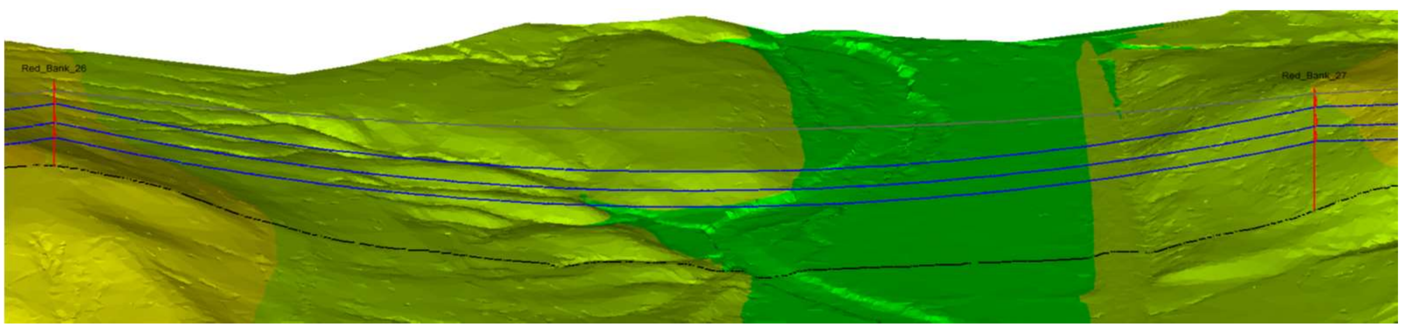
Assumptions of Many Conventional Methods

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



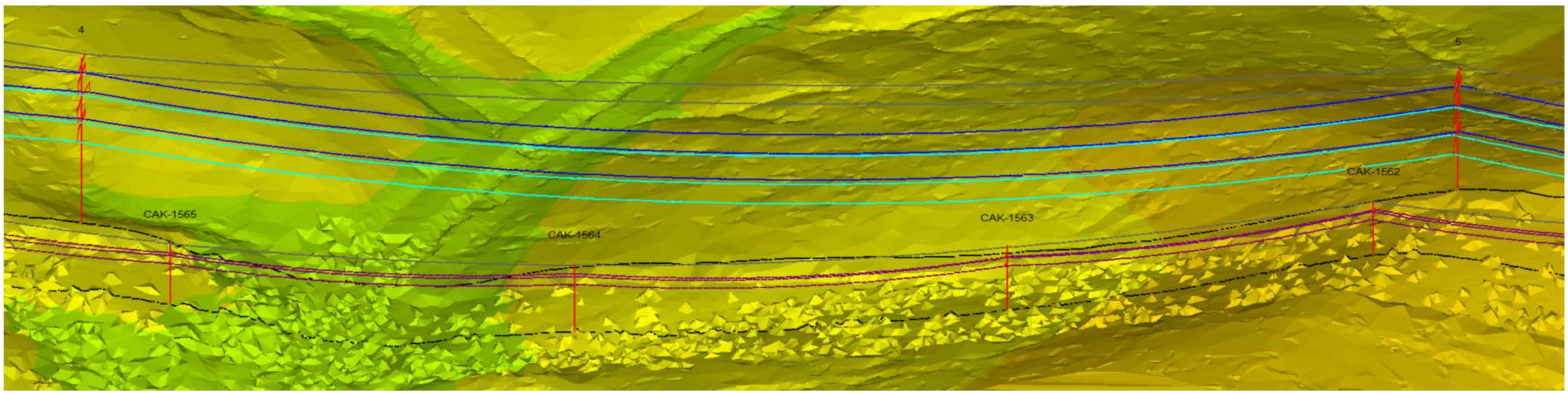
Advantages PLS-CADD

- 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



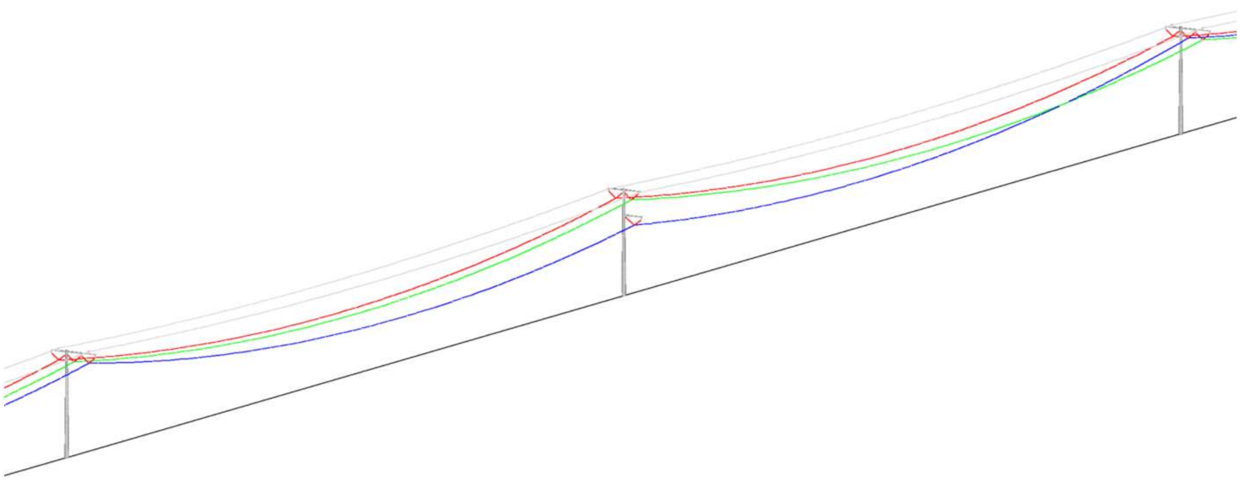
PLS-CADD Structures and Ground

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



PLS-CADD Wires

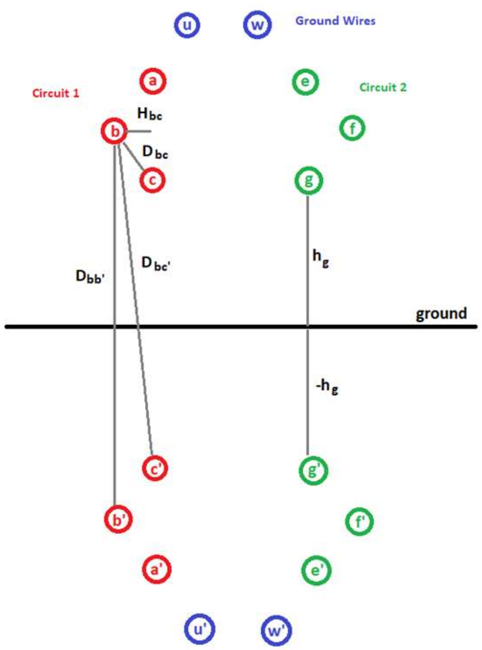
- Every wire and every attachment modeled
- Wire position calculated for operating condition and weather
- Wires have cable properties, phase, and circuit information



Rolling Phases

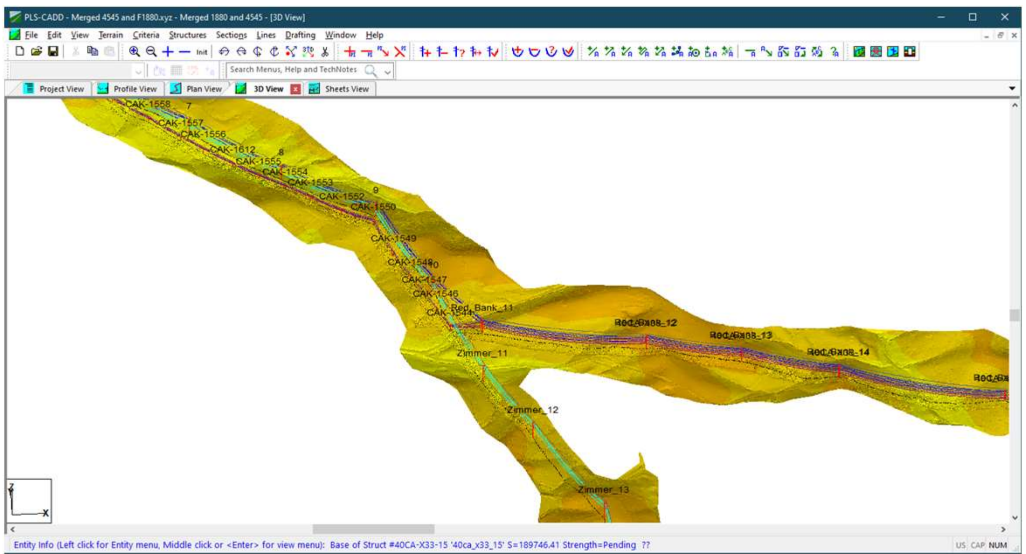
How Line Constants Are Calculated

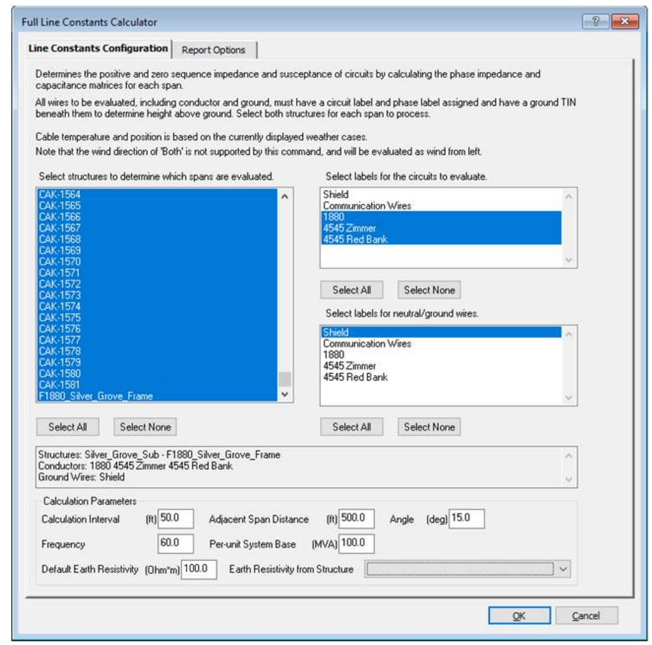
- Impedance is Resistance & Reactance
- Admittance is Conductance (0) & Susceptance
- Cable Properties are Radius, GMR, Resistance
- Distance Between Phases in a Circuit
- Distance Between Phases Between Circuits
- Distance Between Conductors and Grounds
- Height Above Ground
- Earth Resistivity



Intro to PLS-CADD Line Constants

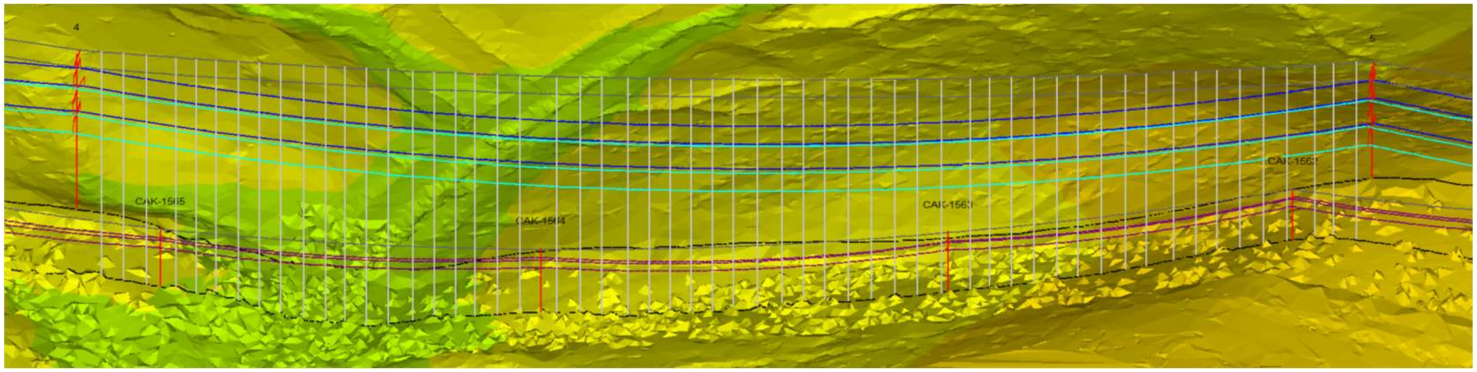
- Almost all required information is already in project
- Define circuits and phases
- Set operating conditions and weather
- Select circuits and range of structures





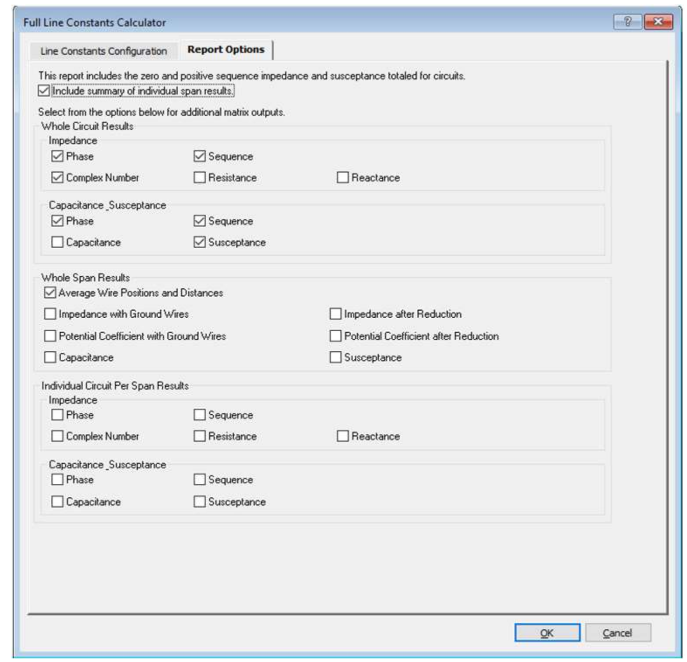
Overview of PLS-CADD Line Constants

- 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

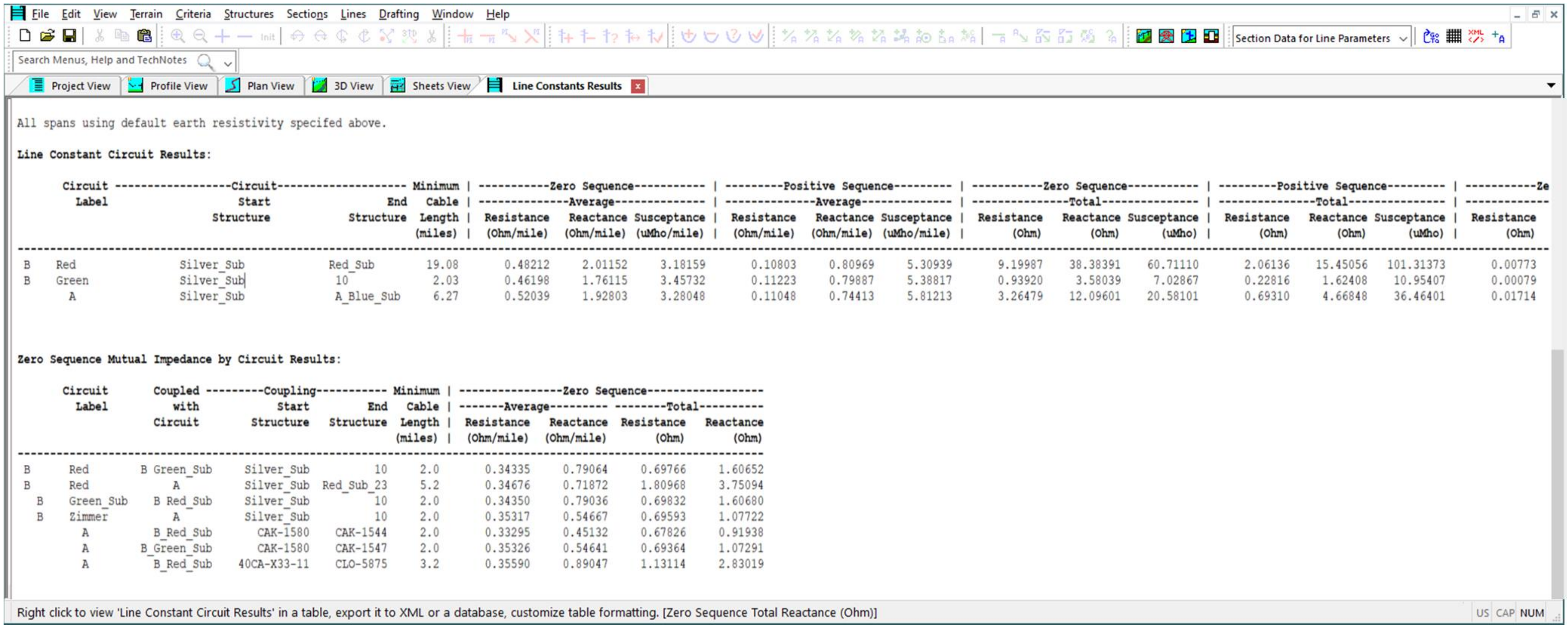


PLS-CADD Line Constants Report

- 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 Report Overview



All spans using default earth resistivity specifed above.

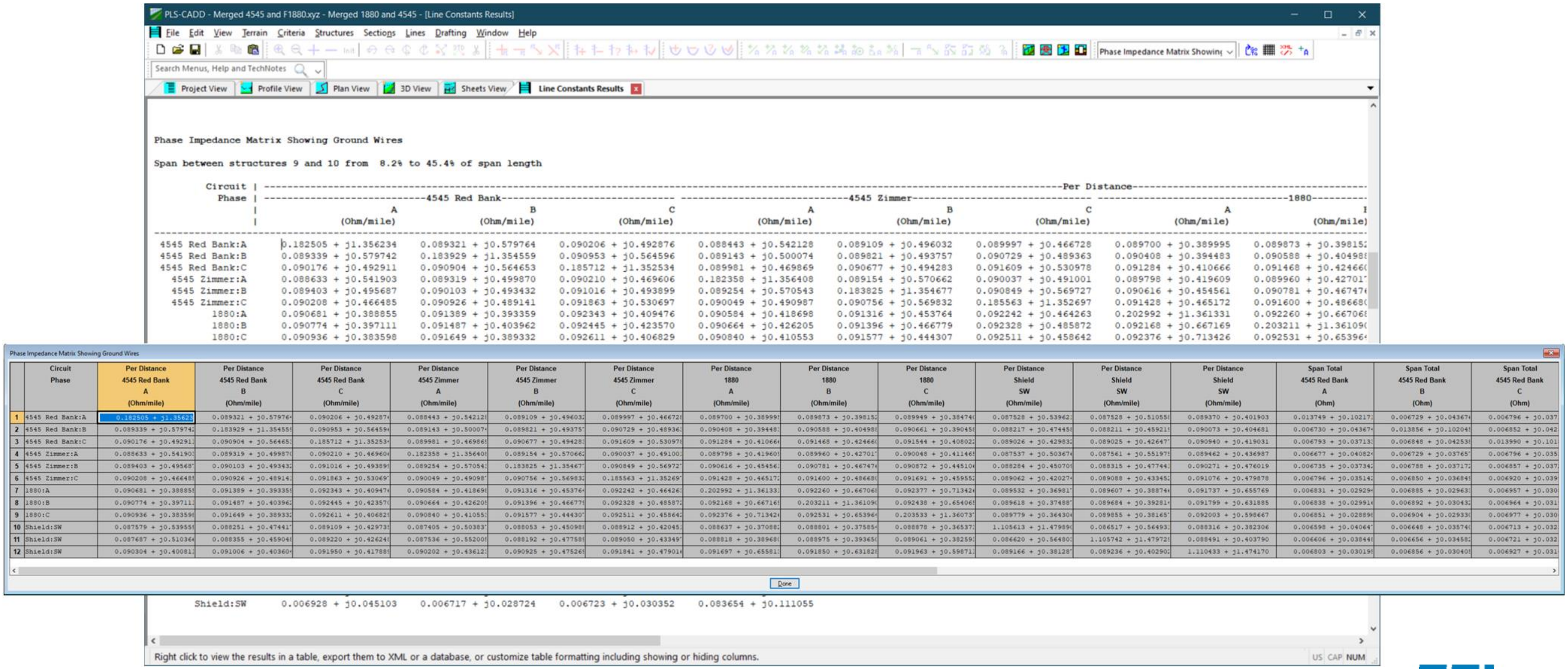
Line Constant Circuit Results:

	Circuit Label	Circuit Start Structure	Circuit End Structure	Minimum Cable Length (miles)	Zero Sequence Average Resistance (Ohm/mile)	Zero Sequence Average Reactance (Ohm/mile)	Zero Sequence Average Susceptance (uMho/mile)	Positive Sequence Average Resistance (Ohm/mile)	Positive Sequence Average Reactance (Ohm/mile)	Positive Sequence Average Susceptance (uMho/mile)	Zero Sequence Total Resistance (Ohm)	Zero Sequence Total Reactance (Ohm)	Zero Sequence Total Susceptance (uMho)	Positive Sequence Total Resistance (Ohm)	Positive Sequence Total Reactance (Ohm)	Positive Sequence Total Susceptance (uMho)	Ze… Resistance (Ohm)
B	Red	Silver_Sub	Red_Sub	19.08	0.48212	2.01152	3.18159	0.10803	0.80969	5.30939	9.19987	38.38391	60.71110	2.06136	15.45056	101.31373	0.00773
B	Green	Silver_Sub	10	2.03	0.46198	1.76115	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	0.52039	1.92803	3.28048	0.11048	0.74413	5.81213	3.26479	12.09601	20.58101	0.69310	4.66848	36.46401	0.01714

Zero Sequence Mutual Impedance by Circuit Results:

	Circuit Label	Coupled with Circuit	Coupling Start Structure	Coupling End Structure	Minimum Cable Length (miles)	Zero Sequence Average Resistance (Ohm/mile)	Zero Sequence Average Reactance (Ohm/mile)	Zero Sequence Total Resistance (Ohm)	Zero Sequence Total Reactance (Ohm)
B	Red	B Green_Sub	Silver_Sub	10	2.0	0.34335	0.79064	0.69766	1.60652
B	Red	A	Silver_Sub	Red_Sub_23	5.2	0.34676	0.71872	1.80968	3.75094
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
	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

Line Constants Matrix Example



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

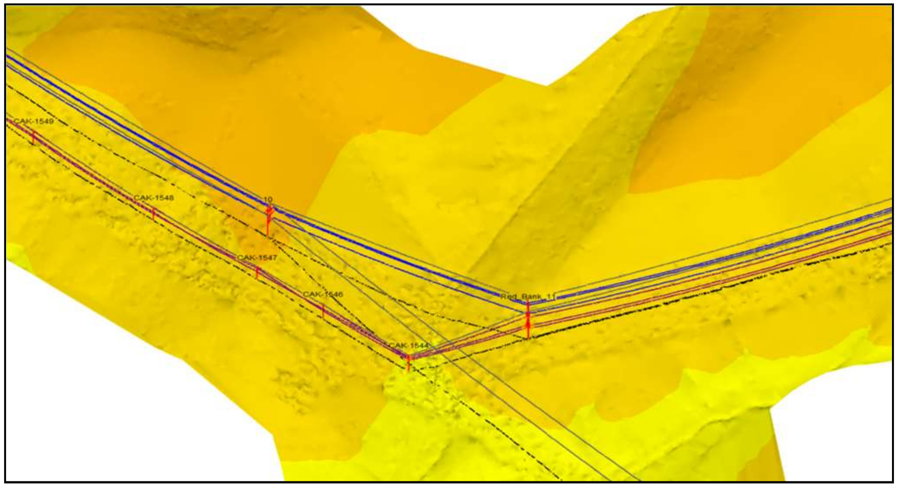
- 138kV Circuit A values were obtained from Excel Calculations
- As a comparison, PLS-CADD Line Constants Calculations were performed to assess the accuracy of the model.
- 138kV Circuit A Values From both Excel & PLS-CADD are shown.

	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

File Edit View Terrain Criteria Structures Sections Lines Drafting Window Help

Section Data for Line Parameters

Search Menus, Help and TechNotes

Project View | Profile View | Plan View | 3D View | Sheets View | Line Constants Results

All spans using default earth resistivity specifed above.

Line Constant Circuit Results:

	Circuit Label	Circuit Start Structure	Circuit End Structure	Minimum Cable Length (miles)	Zero Sequence Average Resistance (Ohm/mile)	Zero Sequence Average Reactance (Ohm/mile)	Zero Sequence Average Susceptance (uMho/mile)	Positive Sequence Average Resistance (Ohm/mile)	Positive Sequence Average Reactance (Ohm/mile)	Positive Sequence Average Susceptance (uMho/mile)	Zero Sequence Total Resistance (Ohm)	Zero Sequence Total Reactance (Ohm)	Zero Sequence Total Susceptance (uMho)	Positive Sequence Total Resistance (Ohm)	Positive Sequence Total Reactance (Ohm)	Positive Sequence Total Susceptance (uMho)	Ze… Resistance (Ohm)
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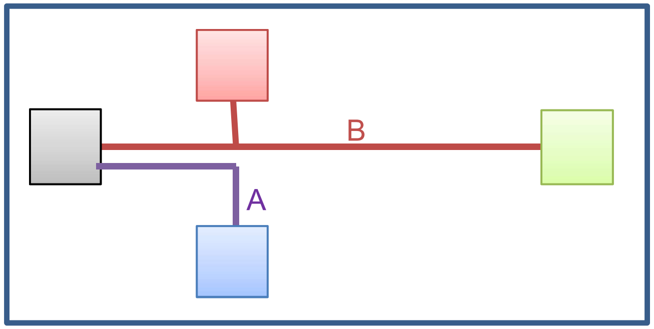


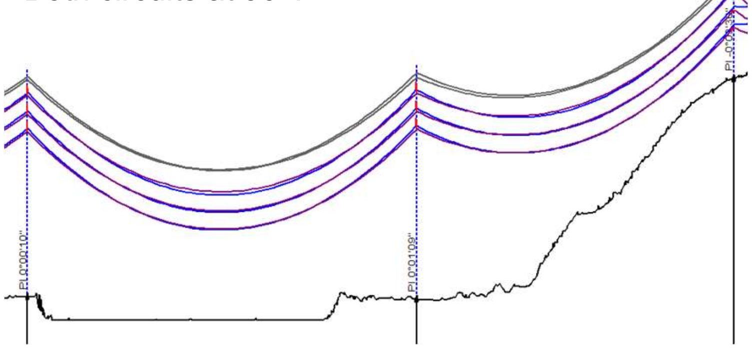
Right click to view 'Line Constant Circuit Results' in a table, export it to XML or a database, customize table formatting. [Zero Sequence Total Reactance (Ohm)]

US CAP NUM

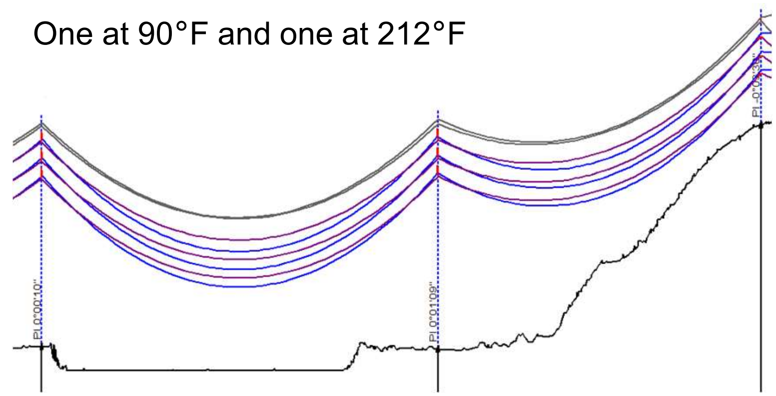
Operating Conditions

- 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

Both circuits at 90°F



One at 90°F and one at 212°F

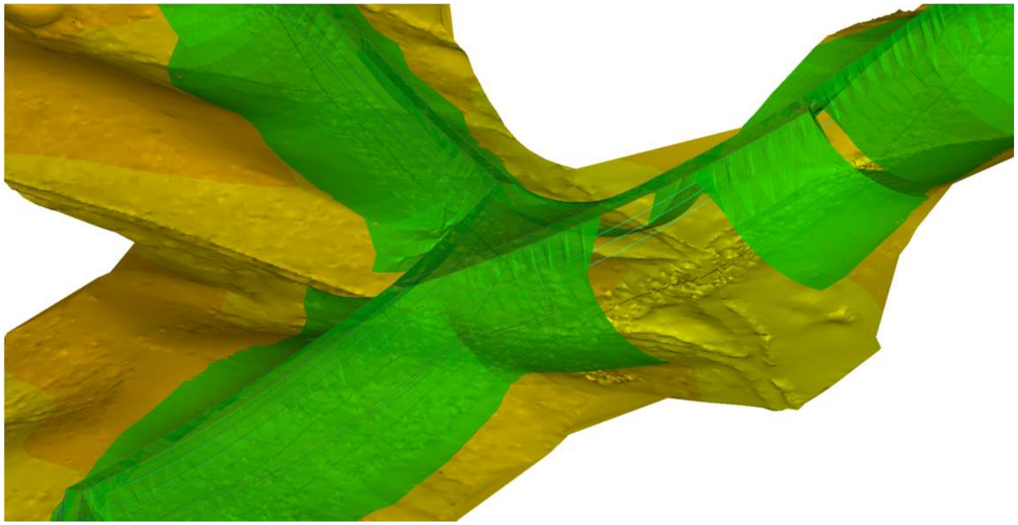


Variable Earth Resistivity

- 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

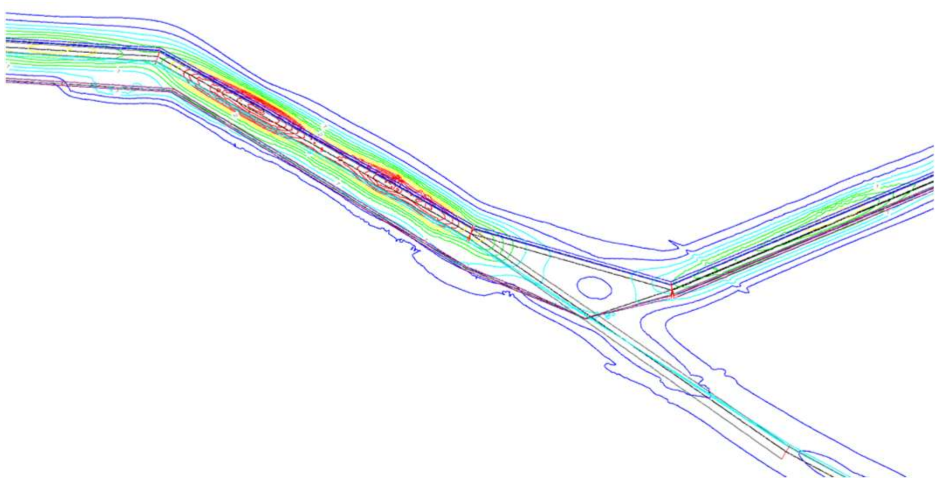
PLS-CADD Lightning Protection

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

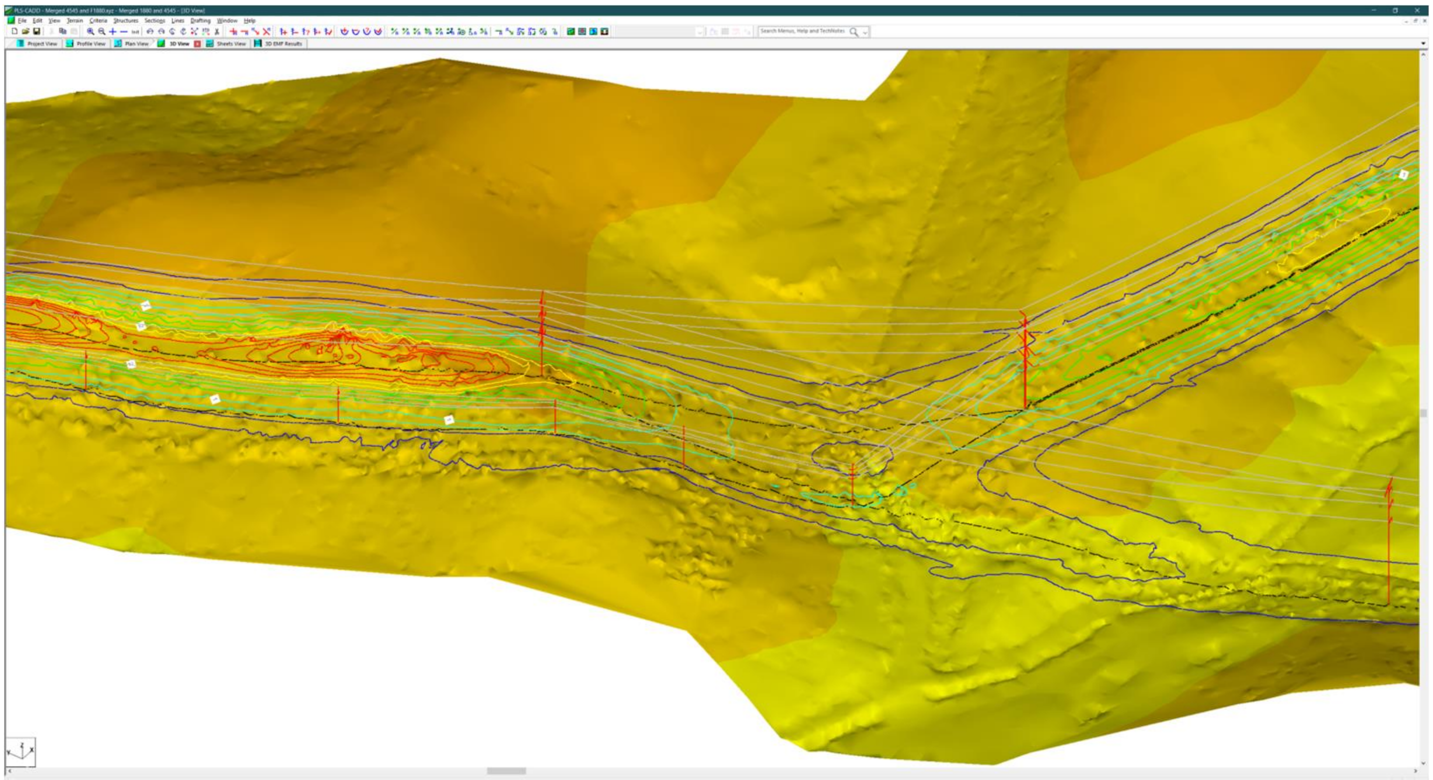


PLS-CADD 3D EMF

- 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: www.powerlinesystems.com
- Email: info@powerlinesystems.com
- Technical Note on the Full Line Constants Feature

POWER LINE® SYSTEMS

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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