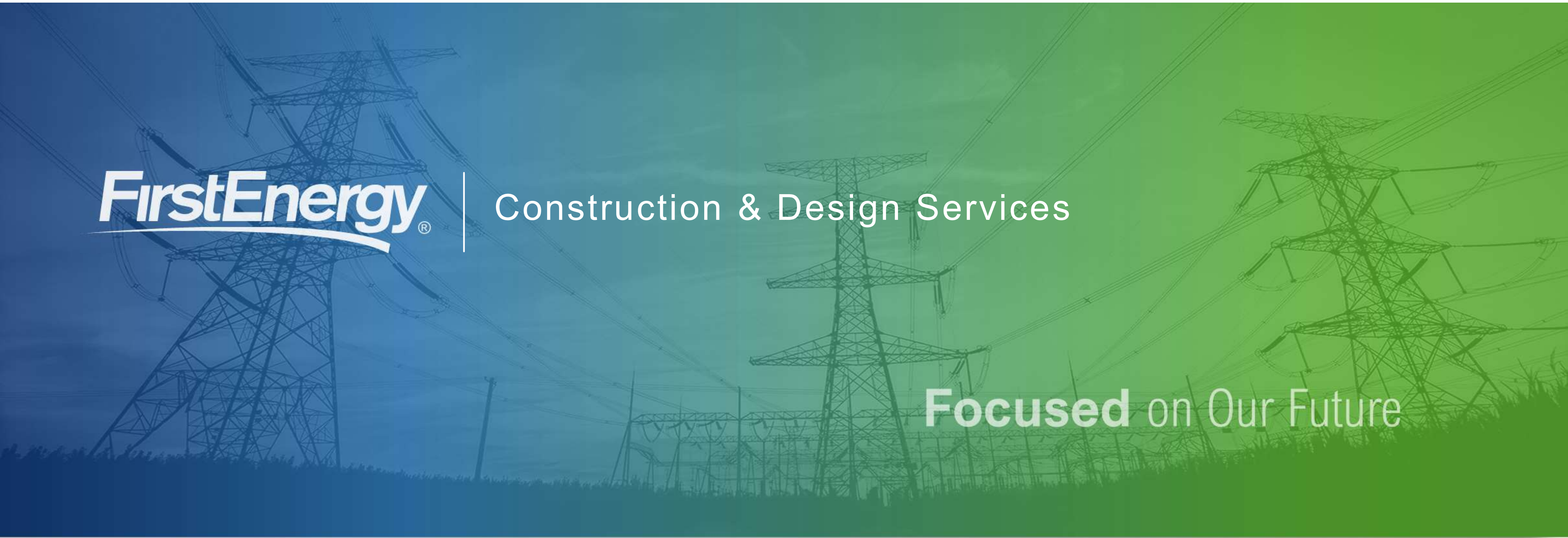

FirstEnergy Transmission Line Lightning Performance Guide Development and Field Application

John Bodenschatz

April 9, 2024

Presentation Outline

- Introduction of the Problem Statement
- FirstEnergy's Current Transmission System Lighting Performance
- Establishing Lightning Performance Design Criteria
- How FirstEnergy is Benefiting from This Work
- Conclusion and Next Steps

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Introduction of the Problem Statement

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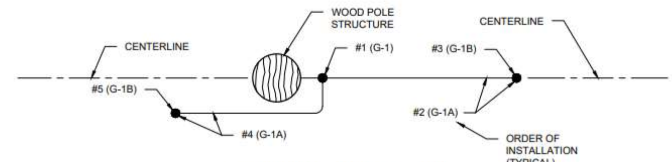
Introduction of the Problem Statement

- FirstEnergy was lacking FirstEnergy specific design criteria for lightning performance.
  - FirstEnergy has one of the largest transmission systems in the United States made up of 10 regional service areas over six states. However,…
    - Companies that formed the FirstEnergy system had a range of design criteria that covered their specific regions which cover a diverse geographical and geological range.
    - Much of the past criteria was not well documented and for some regions it wasn't available.
      - Design structure CFO levels
      - Structure footing resistance requirements
      - Lightning outage performance criteria
      - Structure shielding angles, etc.…
  - There was no known documentation defining lightning outage performance criteria for FirstEnergy transmission lines or the variables used to calculate system performance to benchmark against.
  - A one size fits all approach may not be the best given the territory FirstEnergy covers.

Introduction of the Problem Statement

- FirstEnergy was lacking FirstEnergy specific design criteria for lightning performance.
  - A stringent 10 Ohm footing resistance was a defined criteria.
  - Based on legacy requirement of one of the FirstEnergy Ohio utilities which has relatively low soil resistance.
  - Standard across all FirstEnergy regions.
    - This can be a costly requirement to attain in high resistance areas.
    - Not realistic in rocky terrain up in the hill tops.
    - Adding counterpoise or ground wells unexpectedly during construction can be very costly and lead to cost overruns late in the project life cycle if not accounted for in the design.



GROUND ROD EXTENSION SYSTEM

WOOD POLE GROUND INSTALLATION:

REQUIRED GROUND RESISTANCE IS 10 OHMS OR LESS FOR TRANSMISSION. PROVIDE FINAL GROUND TEST RESULTS TO FIRSTENERGY TRANSMISSION ENGINEER USING PROVIDED TRANSMISSION LINE GROUNDING DATA FORM (SAMPLE ON TR-007000 SHEET 2).

1. INSTALL (1) G-1 GROUND ROD ASSEMBLY, CONSISTING OF TWO GROUND RODS. RECORD GROUND RESISTANCE. IF GROUNDING TEST DOES NOT MEET 10 OHMS, SEE STEP 2.
2. INSTALL (1) G-1A GROUND ROD EXTENSION ASSEMBLY, IN LINE, AHEAD FROM INITIAL GROUND ROD. IF SPECIFIED RESISTANCE IS NOT MET, SEE STEP 3.
3. INSTALL (1) G-1B GROUND ROD EXTENSION ON TOP OF G-1A. IF SPECIFIED RESISTANCE IS NOT MET SEE STEP 4.
4. INSTALL (1) G-1A GROUND ROD EXTENSION ASSEMBLY, IN LINE, BACK FROM INITIAL GROUND ROD. IF SPECIFIED RESISTANCE IS NOT MET, SEE STEP 5.
5. INSTALL (1) G-1B GROUND ROD.

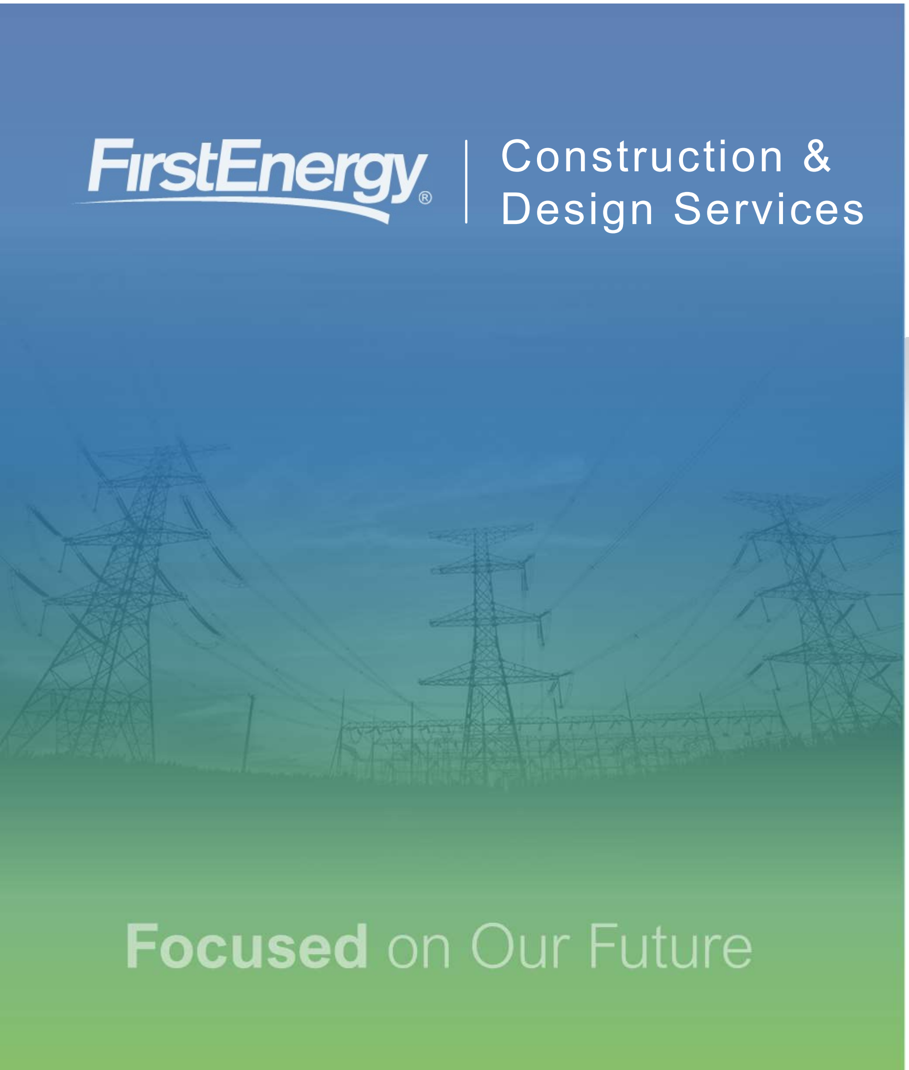
IF GROUND RESISTANCE EXCEEDS 10 OHMS AFTER STEP 5, DETERMINE THE AVERAGE RESISTANCE OF 5 ADJACENT STRUCTURES. IF THE AVERAGE IS UNDER 10 OHMS, DOCUMENT TRANSMISSION LINE GROUNDING DATA FORM AND NO FURTHER GROUNDING IS REQUIRED. IF THIS VALUE IS GREATER THAN 10 OHMS, CONTACT TRANSMISSION ENGINEER FOR FURTHER ACTION.

NOTES:

1. SEE SHEET 2 FOR DETAILS. SEE SHEET 3 FOR BILL OF MATERIAL.
2. WHEN GROUND RODS ARE IN ROCK, CONTACT THE PROJECT ENGINEER OF RECORD FOR GUIDANCE.
3. COUNTERPOISE GROUNDING MAY BE USED IN AREAS OF HIGH SOIL RESISTIVITY OR SHALLOW BEDROCK, OR WHERE LOWER RESISTANCE IS DESIRED; REQUIRES #4 COPPER CLAD STEEL WIRE (40%) BURIED IN EARTH 18" OR GREATER AND A LENGTH OF 100' OR GREATER, LAID APPROXIMATELY STRAIGHT AND PARALLEL WITH CENTERLINE. IF USED, ADD DETAILS TO REMARKS COLUMN OF THE TRANSMISSION LINE GROUNDING DATA FORM.
4. INSTALL ONLY ONE (1) DOWN GROUND FOR BOTH TRANSMISSION AND DISTRIBUTION EQUIPMENT.
5. NOT FOR SWITCH STRUCTURES. SEE TR-007070 FOR SWITCH GROUNDING DETAILS.
6. REFERENCE TR-007090 WHEN DISTRIBUTION UNDERBUILD IS PART OF THE TRANSMISSION STRUCTURE.

REASON FOR REVISION: ADDED NOTE 6 ON SHEET 1.

GROUNDING DETAILS SINGLE WOOD POLE	FirstEnergy Transmission Std.		
	DATE ISSUED: 08/26/2020		
	DWG NO. TR-007010	SHEET 1 / 3	REV. 2.1



Current Transmission System Lighting Performance

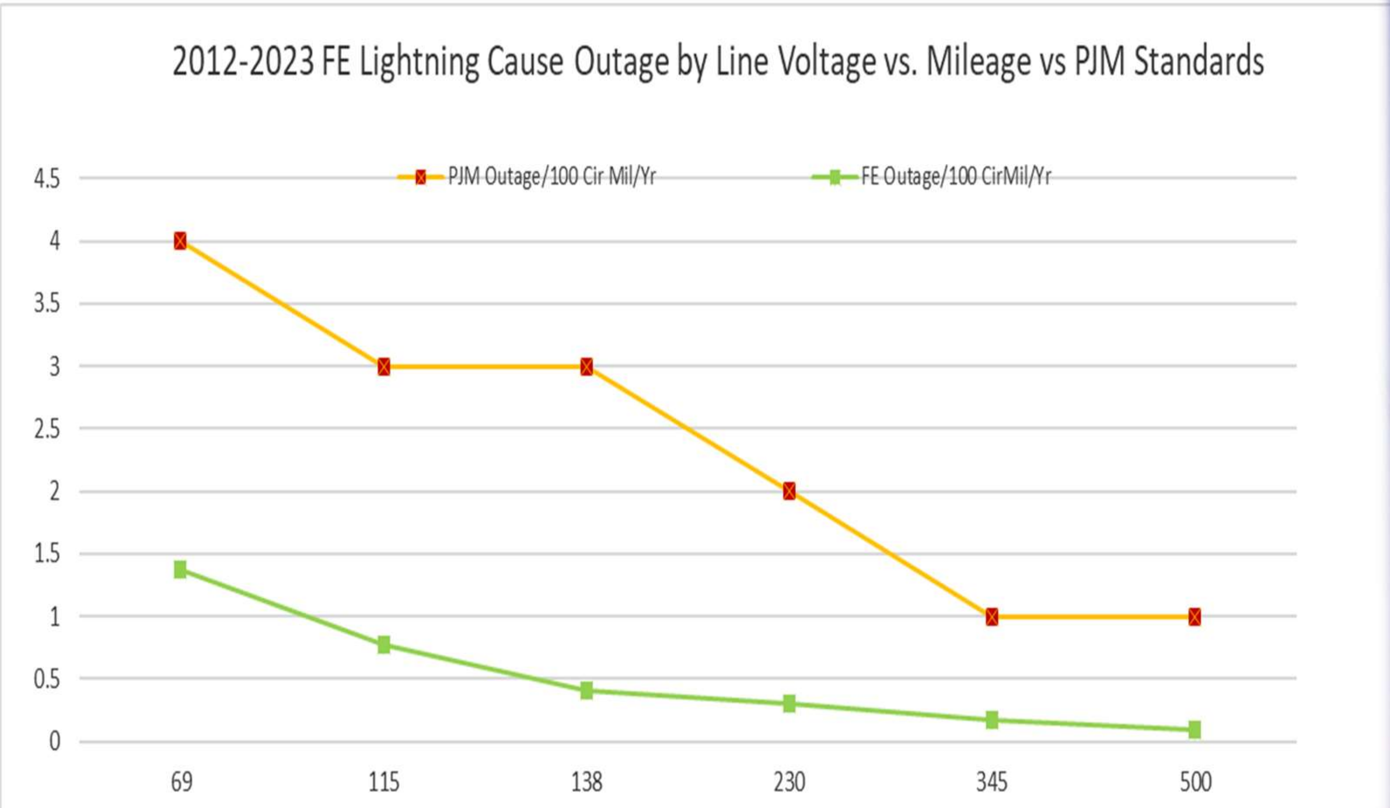
What is FirstEnergy's Current Transmission System Lighting Performance

- Needed to know where we currently stand to measure improvement.
  - 2012-2023 FE Lightning Cause Outage by Line Voltage vs. Mileage vs. PJM Standards

Voltage Level	Outage	Outage(%)	Total Line Mileage	Total Line Mileage (%)	FE Outage/100 CirMil/Yr	PJM Outage/100 Cir Mil/Yr	Outage/100 CirMil/Yr vs.PJM Standard
69	444	44%	3225	18%	1.4	4	34%
115	149	15%	1924	11%	0.8	3	26%
138	313	31%	7766	43%	0.4	3	13%
230	57	6%	1914	11%	0.3	2	15%
345	27	3%	1597	9%	0.2	1	17%
500	14	1%	1441	8%	0.1	1	10%
Grand Total	**1004**	**100%**	**17867**	**100%**	**0.5**		

What is FirstEnergy's Current Transmission System Lighting Performance

- Need to know where we currently stand to measure improvement.



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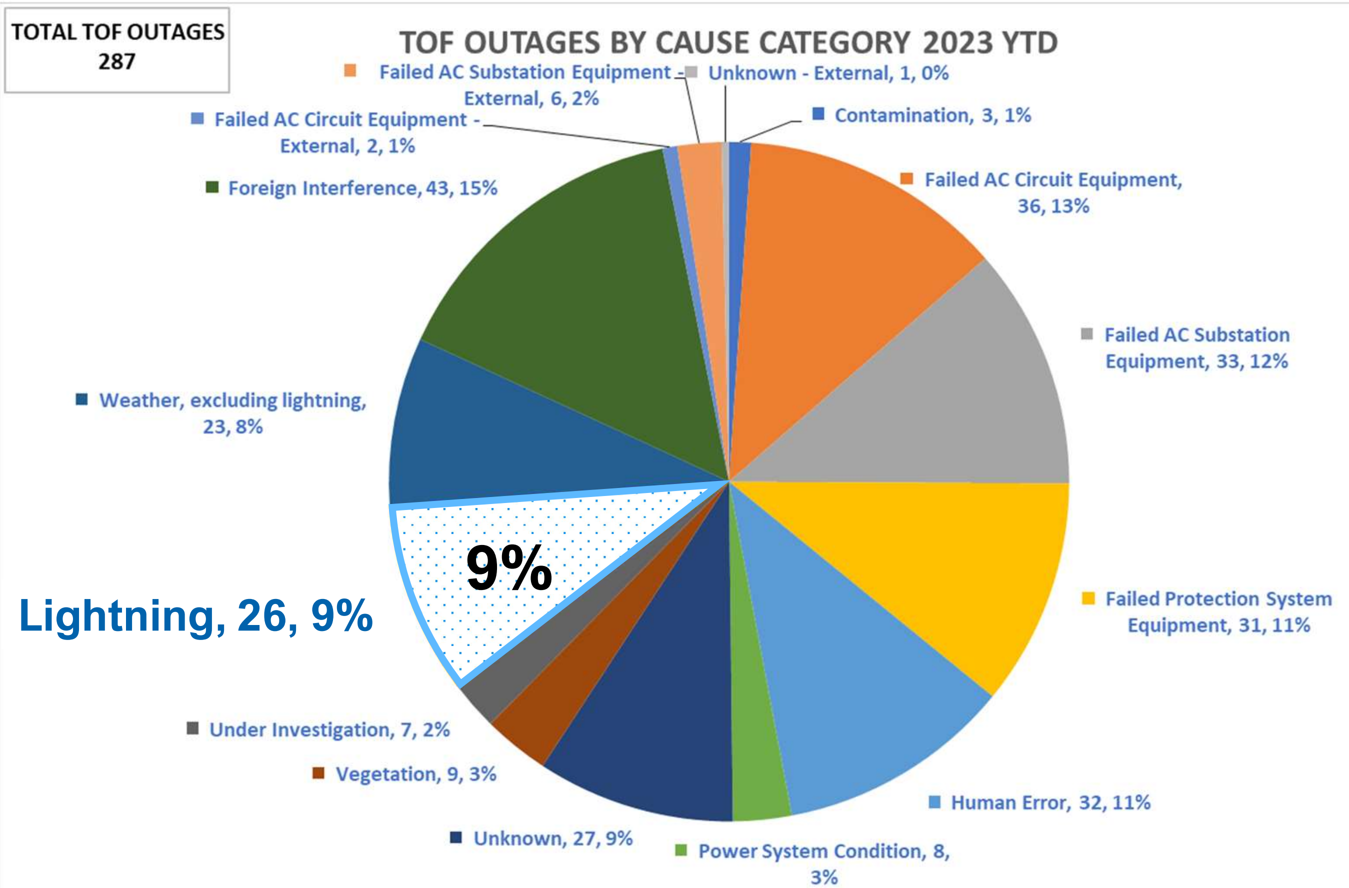
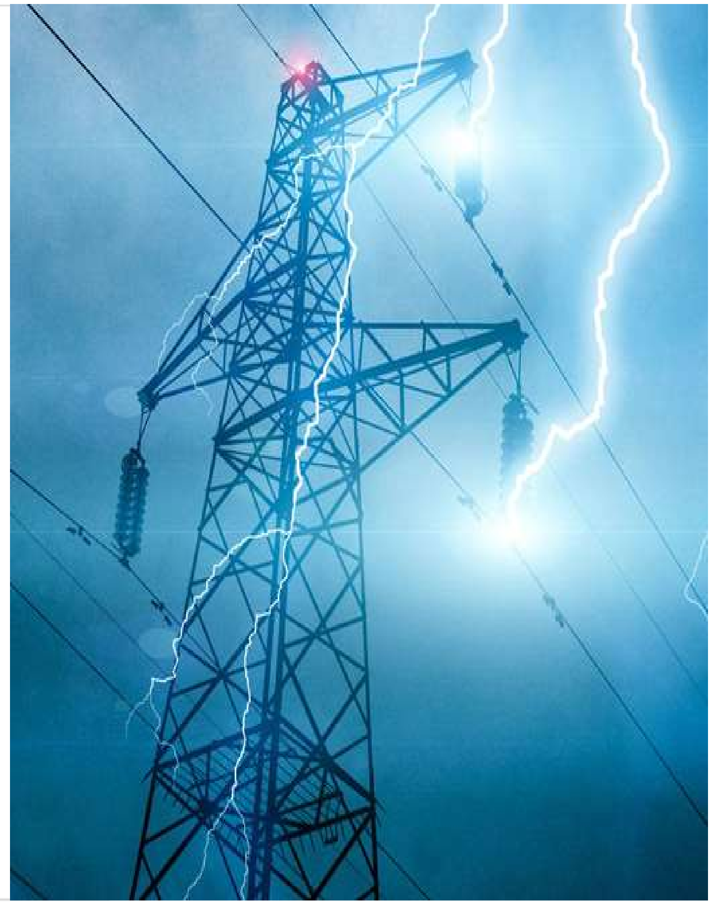
2023 Lightning Caused Outages vs. Other Outages >100 kV





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Establishing Lightning Performance Design Criteria

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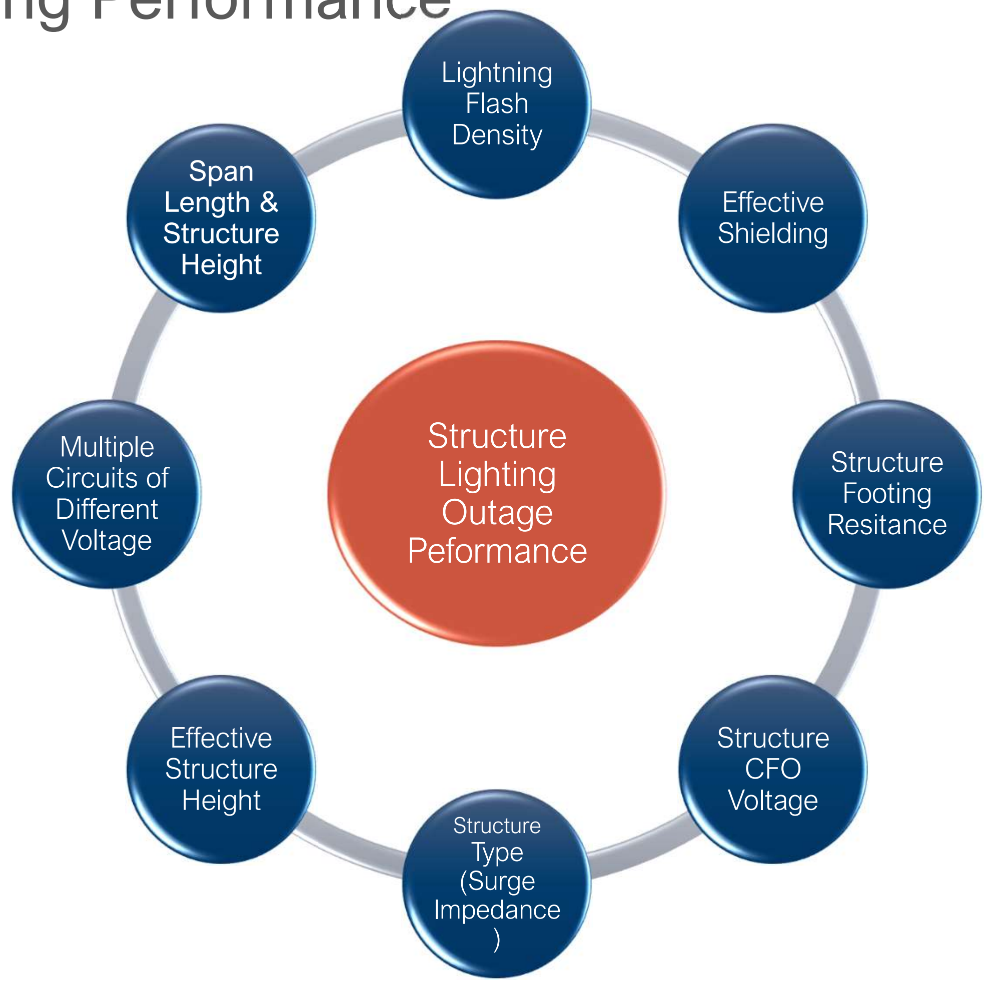
Considerations for Structure Lightning Performance

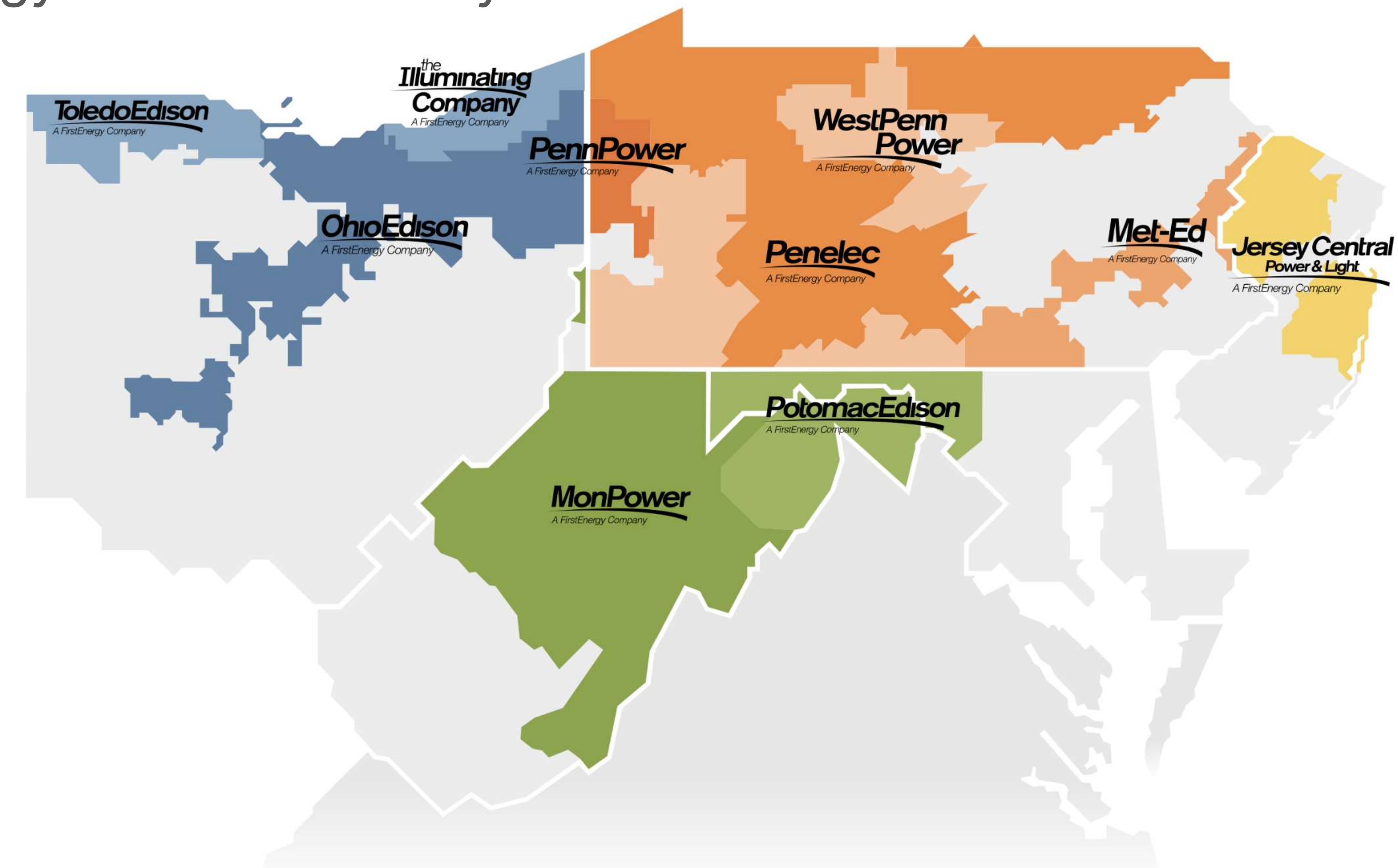
- Balancing Act of Many Inputs
  - Where do you start?
  - Highly iterative given FirstEnergy's diverse geography and system voltages.
    - No one type fits all solution.
  - Shotgun vs. rifle approach.
    - Standards Design vs. Project Specific.
  - Criteria can greatly influence cost.
    - Sometimes with little benefits.



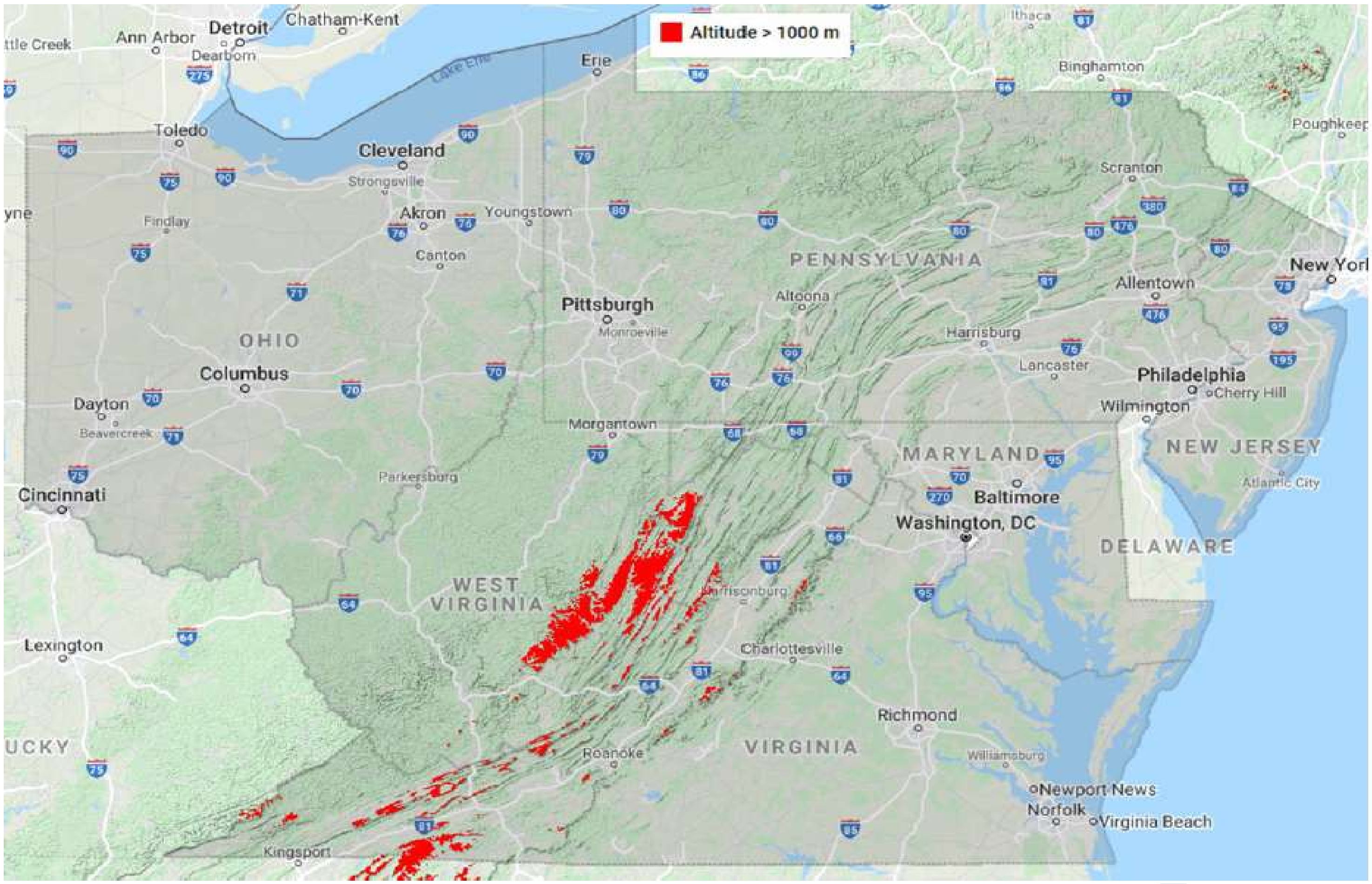
Where do we start to establish design criteria and calculation guide?

- You don't know what you don't know!
  - It started with seeking proposals from large design firms.
    - Red flags based on the questions being asked about the software.
  - Rebooted and went to EPRI (Electric Power Research Institute) the firm that distributes the TFLASH lightning performance software.
    - Established a design guide with criteria looking at the highest lightning density.
    - Evaluated 10 of structure series as part of the effort
    - Provide both theory and hands on TFLASH training workshops.

FirstEnergy Service Territory

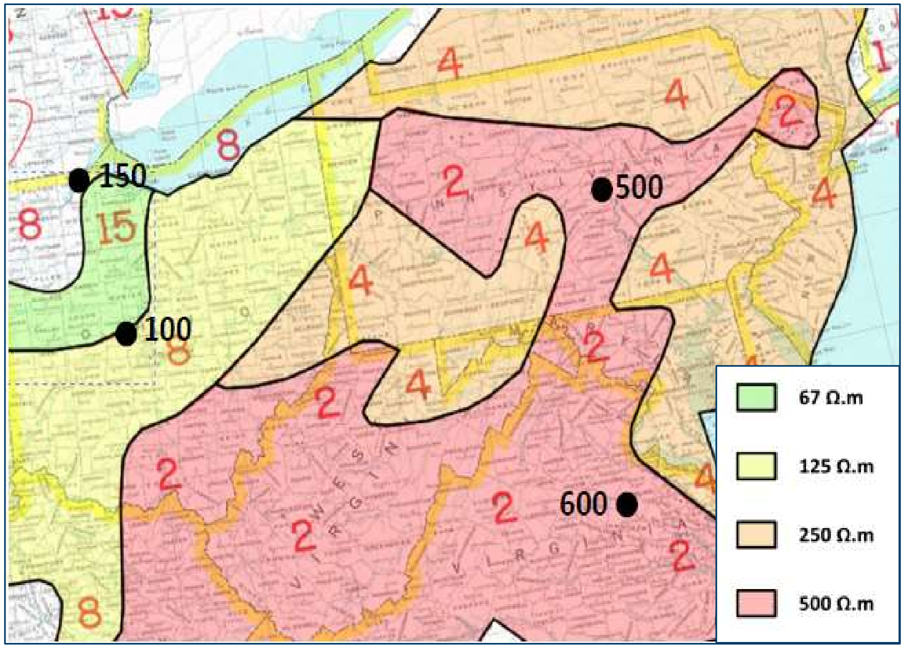


FirstEnergy Service Territory Areas Above 3,280 Feet

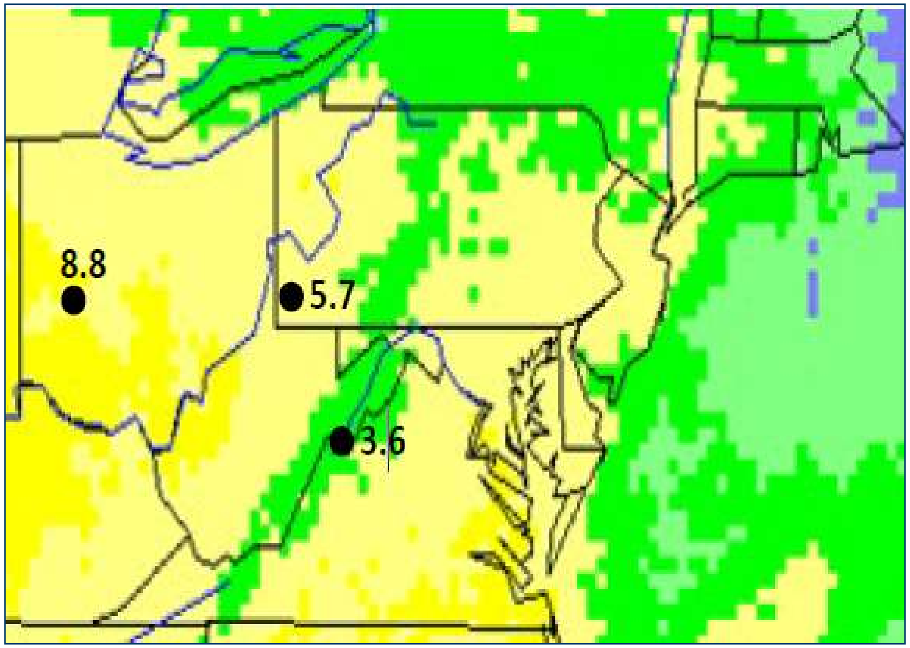


FirstEnergy Service Territory

Overview of expected ground resistances

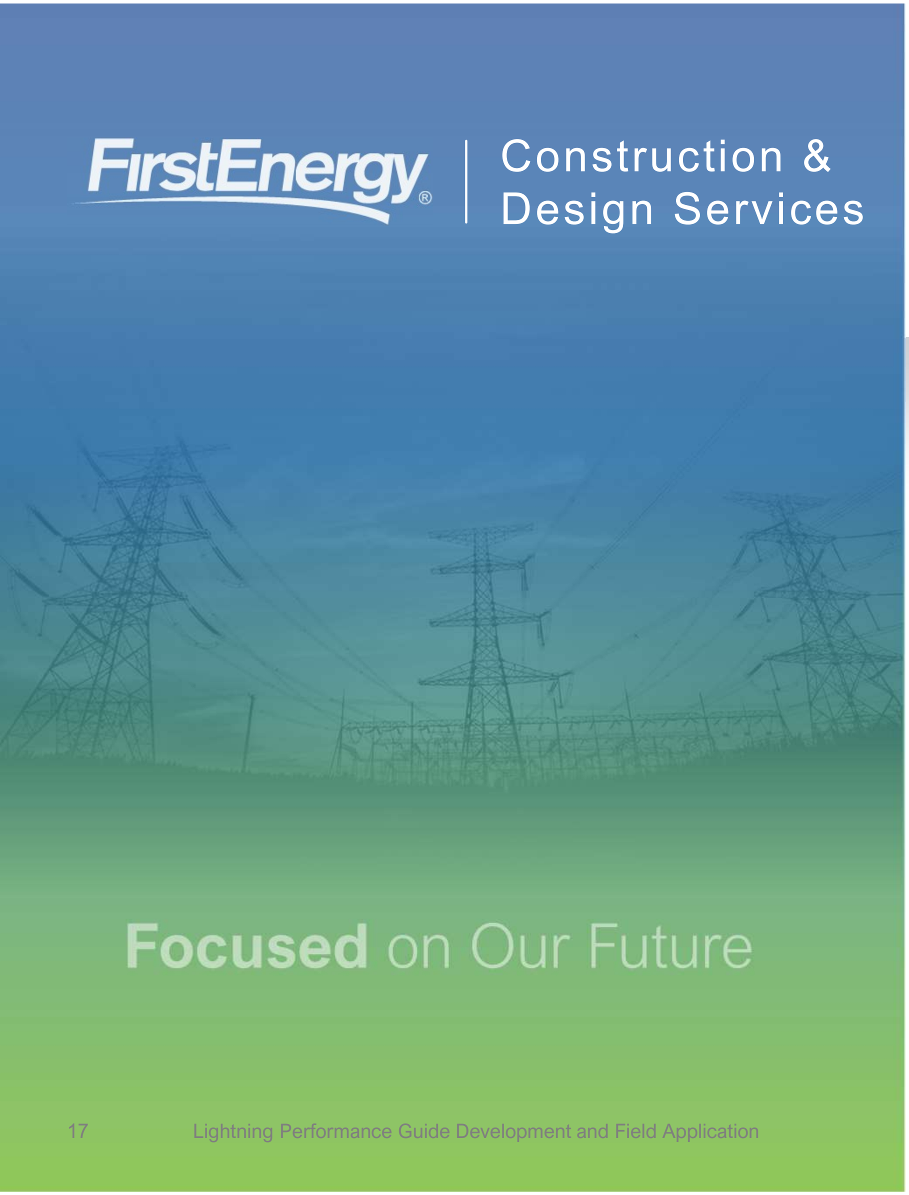


Lighting density map. Flashes / sq. mi. / year



Outage Performance Targets and Other Criteria

System Voltage	69 kV	115 kV	138 kV	230 kV	345 kV	500 kV
Target Lightning Outage Rate (outages/100 circuit-miles / yr)	3	3	3	2	1	1
PJM's Minimum Critical Flashover voltage (kV)	440	670	860	1105	1440	2145
PJM's Maximum Footing Resistance (Ω)	25	25	25	25	15	15
FE's Maximum Footing Resistance (Ω)	10	10	10	10	10	10



How FirstEnergy is Benefiting from This Work: Example 1

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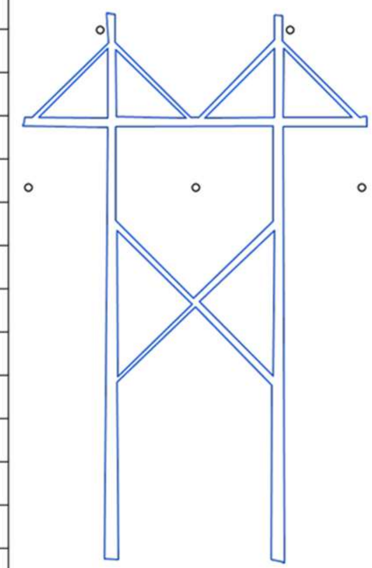
Example of a Deficiency Fixed in a Standard Structure

- A deficiency was identified in the standard H-frame designs which are a common construction type for FirstEnergy.
  - Structure was evaluated based on the current design standard.

Table 3-13
Details of the single circuit 138 kV line studied

Voltage:	138 kV
No. Circuits:	1
Configuration:	Horizontal
No. Shieldwires:	2
FE-Reference:	TR-138045
Structure type:	Grounded wood pole
Structure Surge impedance:	262 Ω
Insulation type:	I-Suspension polymer insulator
Critical Flashover Voltage:	708 kV
Span Length:	760 ft
Height of Tower:	82.1 ft
Phase spacing:	15.5 ft
Height of lowest phase	64.6 ft
Range of footing resistance	3.4 Ω – 53 Ω



Example of a Deficiency Fixed in a Standard Structure

- The analysis showed it is difficult to hit the performance criteria based on the current design.
  - A high structure surge impedance in combination with relatively tall structures contributes to high back flashover rates even with low footing resistances.
  - Longer span lengths with this type of structure also contributed to high back flashover rates.
- Difficult to change these variables.

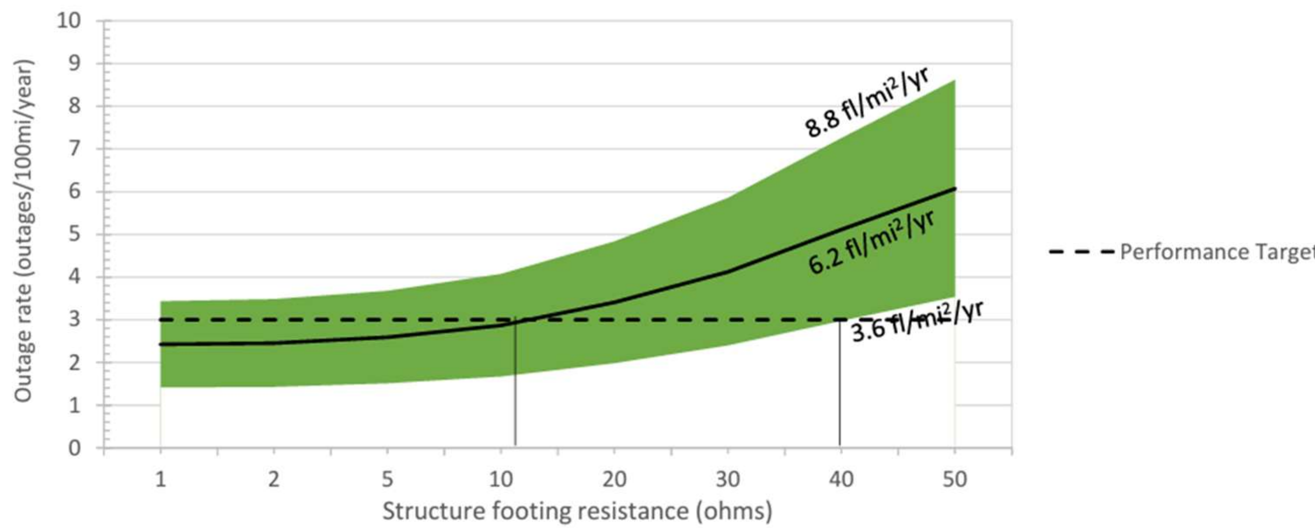


Figure 3-26
Predicted outage range for Ground Flash Density in operating territory

Example of a Deficiency Fixed in a Standard Structure

- Span lengths and structure height considered fixed variables.
- Consider changing another part of the structures design to improve lightning performance
  - Original design used polymer I-string insulators.
  - Proposed using porcelain/glass insulator I-strings of the same length of the polymer insulators.
    - Increased the CFO of the structure.
      - 708 kV with Polymer insulators.
      - 972 kV with porcelain/glass insulators.

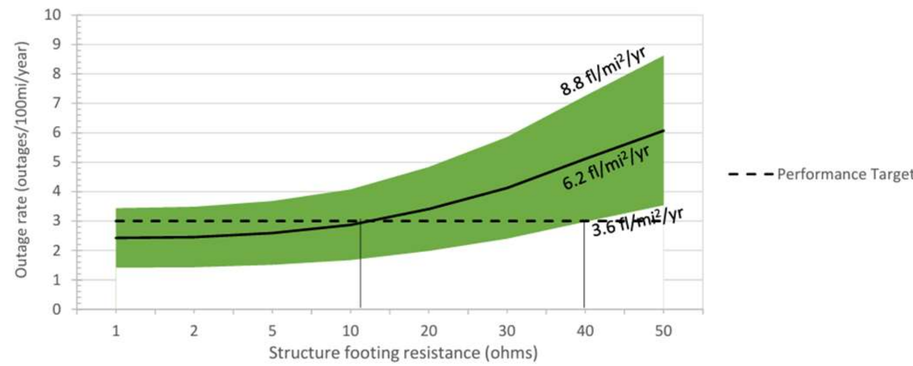


Figure 3-26
Predicted outage range for Ground Flash Density in operating territory

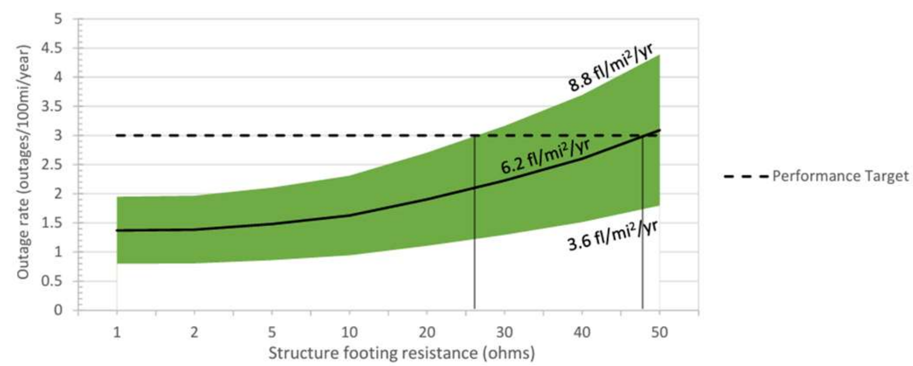


Figure 3-28
Predicted outage range of the modified 138 kV single circuit line with an improved insulation level for the Ground Flash Density in operating territory

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How FirstEnergy is Benefiting from This Work: Example 2

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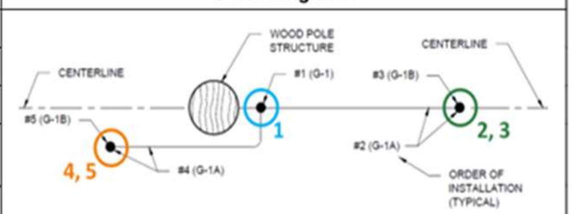
Example of Field Adjustments Based on Site Specific Criteria

- Example of single circuit 69 kV horizontal post structure.
  - The most common structure type was evaluated.
  - The average span length and structure height were used for the performance calculations.

Table 3-21
Details of the ground electrode typically employed on 69 kV single wood pole structures

	Action	Grounding Plan
1	1x16'	
2	1x16' + 1x(1x10' + 1x8')	
3	1x16' + 1x(1x10' + 1x16')	
4	1x16' + 1x(1x10' + 1x16') + 1x(1x10' + 1x8')	
5	1x16' + 2x(1x10' + 1x16')	

69 kV Lines

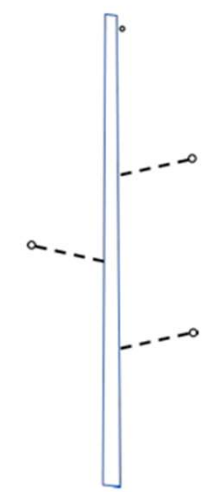
The lightning performance of a representative single and double circuit 69 kV line configuration was studied in detail.

69 kV Single circuit, delta configuration

Line characteristics

Pertinent details of the single circuit 69 kV line studied are summarized in Table 3-20, the detailed input data and dimensions are provided in Appendix B. Details of a typical ground electrode for 69 kV wood pole lines are presented in Table 3-21.

Table 3-20
Details of the single circuit 69 kV line studied

Voltage:	69 kV	
No. Circuits:	1	
Configuration:	Delta	
No. Shieldwires:	1	
FE-Reference:	TR-069010	
Structure type:	Wood-pole	
Structure Surge impedance:	390 Ω	
Insulation type:	Polymer line post + wood	
Critical Flashover Voltage:	600 kV (759 kV)	
Span Length:	300 ft	
Height of Tower:	53.5 ft	
Phase spacing:	10.3 ft	
Height of lowest phase	37.5 ft	
Range of footing resistance	8.4 Ω – 105 Ω	

Typical Chart from a Parametric Study

- Various parametric studies were run for the most common structure to show how changes to various input variable changed the structure outage performance.
- Figure 3-40 shows how the change in the footing resistance impacts the structure outage performance.
  - Note that this chart is based on 10 flashes / mi.^{2} / year

Results

The results of the reference performance calculation are presented in Figure 3-40:

- Shielding failures do occur but are not a dominant cause of outages.
- Backflashovers are the dominant cause of lightning outages over the whole range of footing resistance values.
- Reducing the footing resistance below 10 Ω does not result in a further reduction of the line performance. This is due to the relatively high surge impedance of the ground wire along the wood pole that conducts the lightning current to ground.

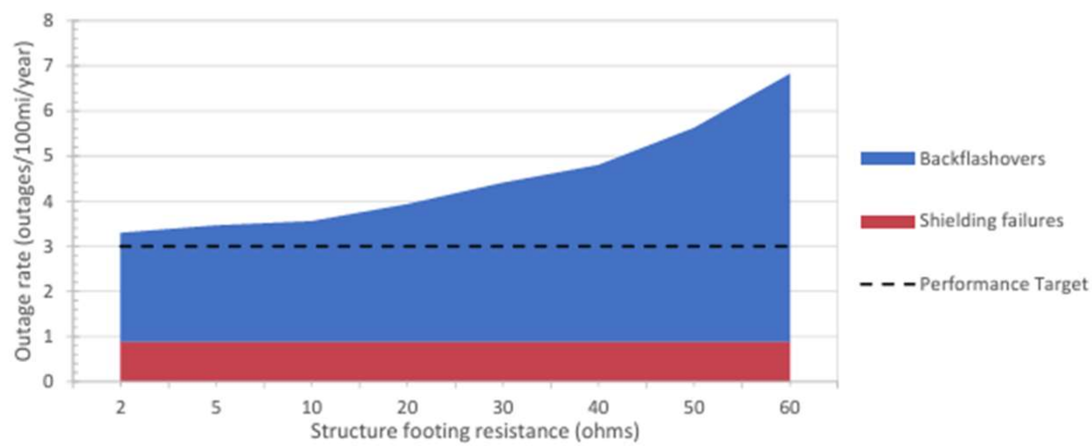


Figure 3-40
Reference performance calculation: Ground Flash Density: 10 fl/mi²/yr

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Parametric Results of Actual Ground Flash Density vs. Footing Resistance

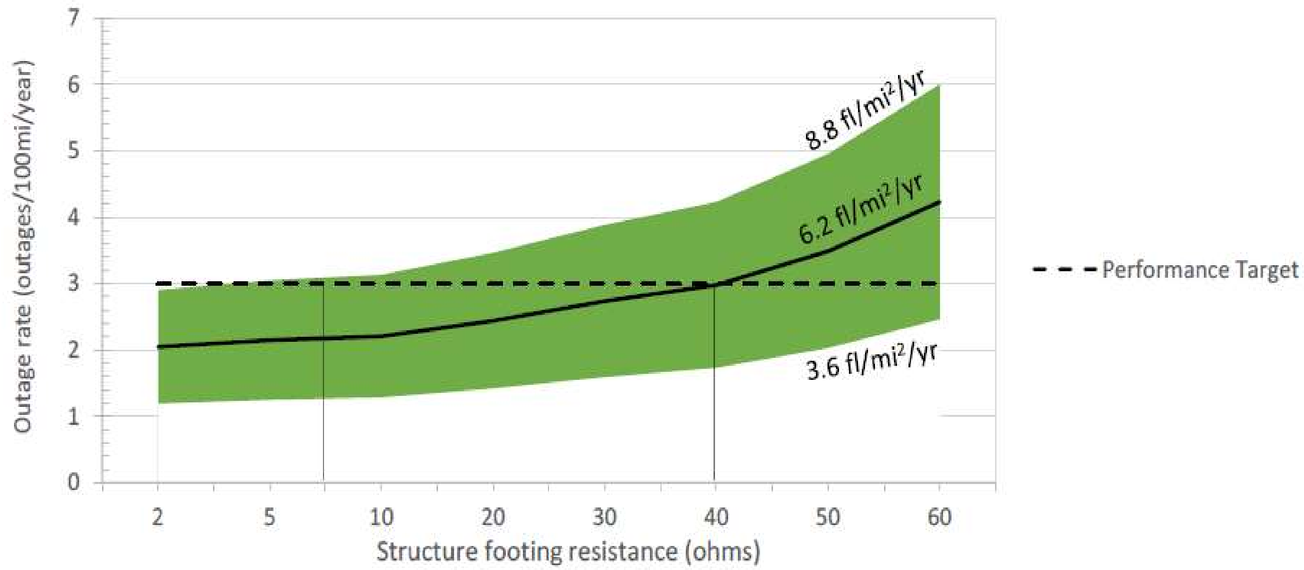
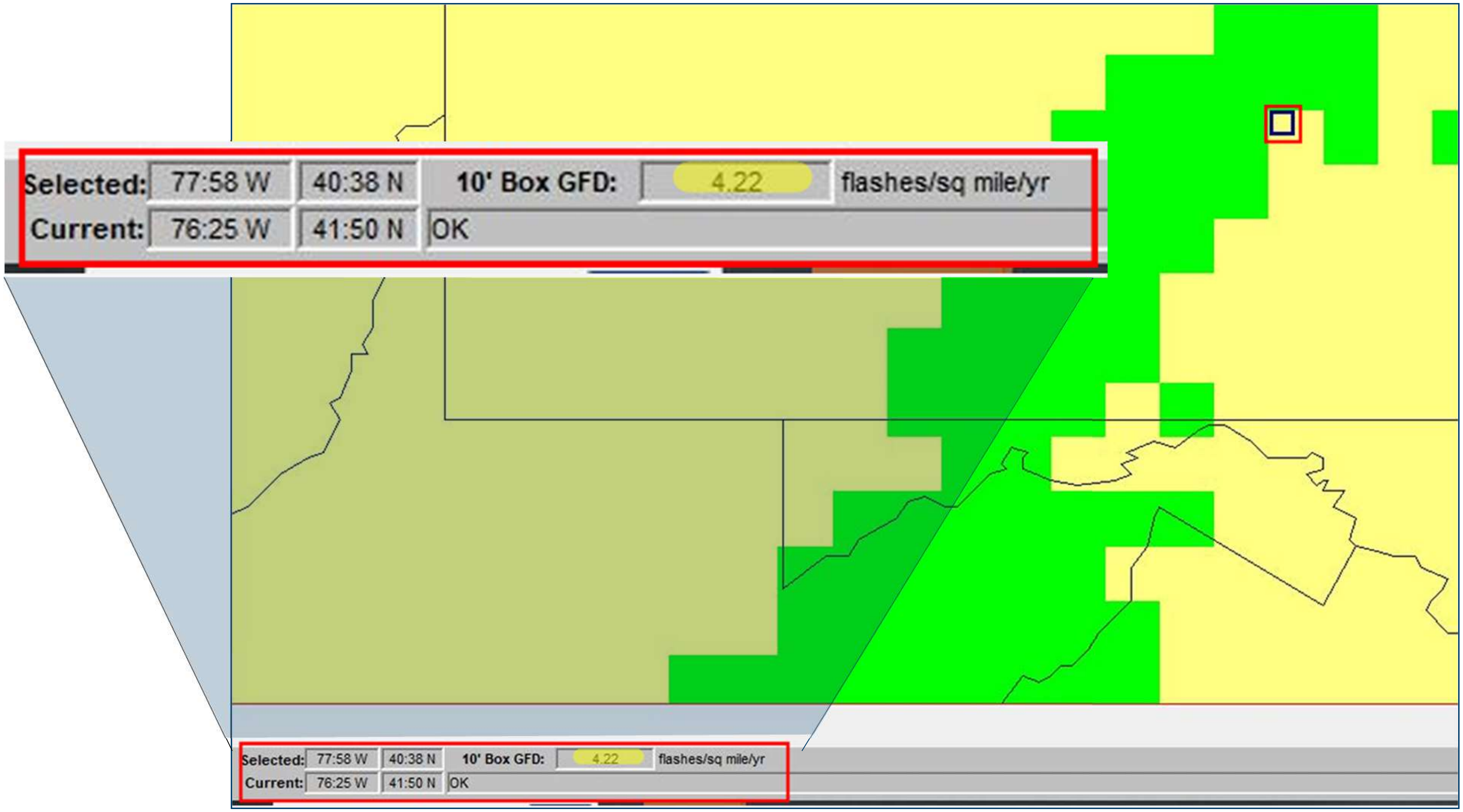


Figure 3-41
Predicted outage range for Ground Flash Density in operating territory

Ground Flash Density Map from TFLASH



Compare of Actual Ground Flash Density vs. Footing Resistance

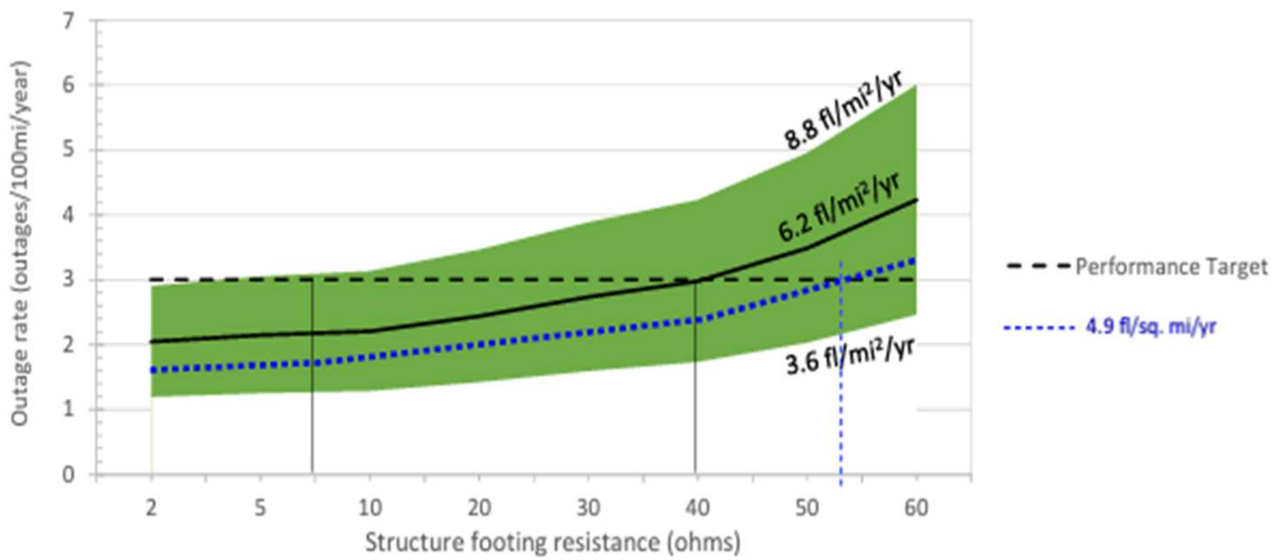


Figure 3-41
Predicted outage range for Ground Flash Density in operating territory

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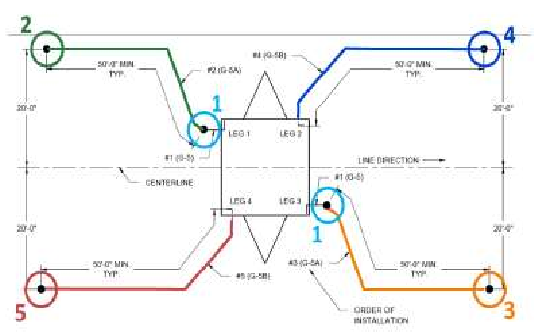
How FirstEnergy is Benefiting from This Work: Example 3

Example of 500 kV Lattice Tower Grounding vs. Footing Resistance

- Example of single circuit 500 kV horizontal lattice tower structure.
  - The most common structure type was evaluated.
  - The average span length and structure height were used for the performance calculations.

Table 3-3
Details of the ground electrode typically employed at 500 kV self-supporting lattice structures

	Action	Grounding Plan
1	2x16'	
2	2x16' + 1x(1x50' + 1x16')	
3	2x16' + 2x(1x50' + 1x16')	
4	2x16' + 3x(1x50' + 1x16')	
5	2x16' + 4x(1x50' + 1x16')	
alt	2x16' + 4x50'	
	Note: For the alternative configuration, no rods are applied at the end of the horizontal conductors.	

500 kV Line

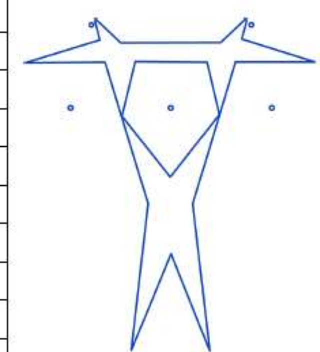
The lightning performance of one 500 kV line configuration was studied in detail.

Single circuit, horizontal configuration

Line characteristics

Pertinent characteristics of the chosen representative single circuit 500 kV line are summarized in Table 3-2. The detailed input data and dimensions are provided in Appendix B. Details of the typical ground electrode used at 500 kV self-supporting lattice towers are presented in Table 3-3.

Table 3-2
Details of the single circuit 500 kV line studied

Voltage:	500 kV	
No. Circuits:	1	
Configuration:	Horizontal	
No. Shieldwires:	2	
FE-Reference:	5S2-8 marked as ST	
Structure type:	Lattice	
Structure Surge impedance:	97.86 Ω	
Insulation type:	Suspension disc Vee string	
Critical Flashover Voltage:	2120 kV	
Span Length:	1250 ft	
Height of Tower:	138.5 ft	
Phase spacing:	31.5 ft	
Height of lowest phase	111.8 ft	
Range of footing resistance	3.4 Ω – 53 Ω	

Example of 500 kV Lattice Tower Grounding vs. Footing Resistance

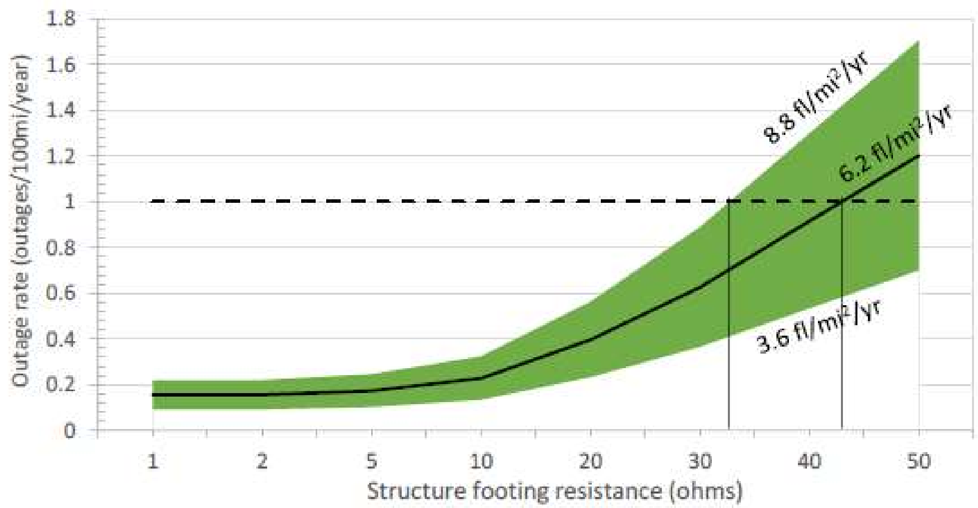


Figure 3-2
Predicted outage range for Ground Flash Density in operating territory

- Outage Rate vs. Footing Resistance for a Range of Flash Densities.
  - Structure performs very well compared to lower voltage structures due to the high CFO based on the required insulator for an EHV line.
  - Lattice Towers have a much lower structure surge impedance than monopoles.
  - The heights of the structures and span lengths hurt performance.

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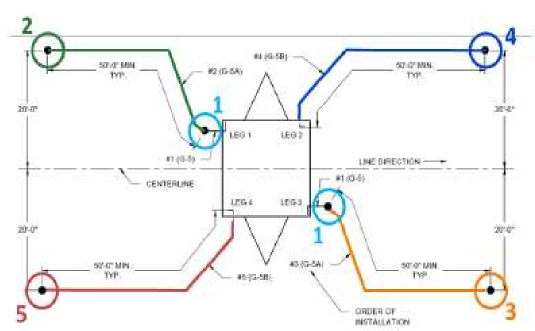
Example of 500 kV Lattice Tower Grounding vs. Footing Resistance

Table 3-3
Details of the ground electrode typically employed at 500 kV self-supporting lattice structures

	Action	Grounding Plan
1	2x16'	
2	2x16' + 1x(1x50' + 1x16')	
3	2x16' + 2x(1x50' + 1x16')	
4	2x16' + 3x(1x50' + 1x16')	
5	2x16' + 4x(1x50' + 1x16')	
alt	2x16' + 4x50'	
	Note: For the alternative configuration, no rods are applied at the end of the horizontal conductors.	

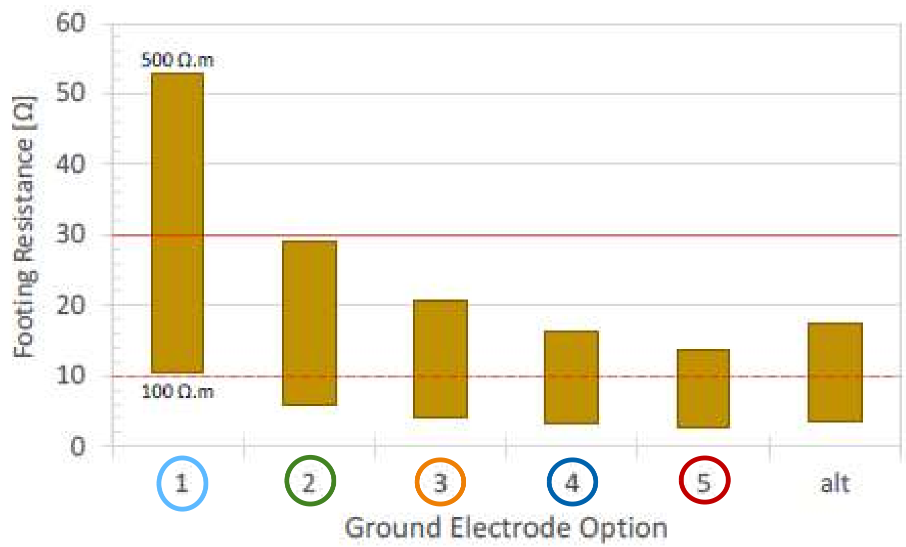


Figure 3-3
Calculated footing impedance at 60 Hz for the expected range of soil resistivities.

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Example of 500 kV Lattice Tower Grounding vs. Footing Resistance

- Impact of grounding requirements vs. structure footing resistance.
  - First, the 10 Ohm footing resistance target is unattainable with the current grounding standards for soil resistivity above 360 Ohm*meters.
    - Recommendation is to allow a 30 Ohm footing resistance.
  - Second, the figure enables the design team to estimate the amount of grounding needed based on the anticipated or measured soil resistivity.

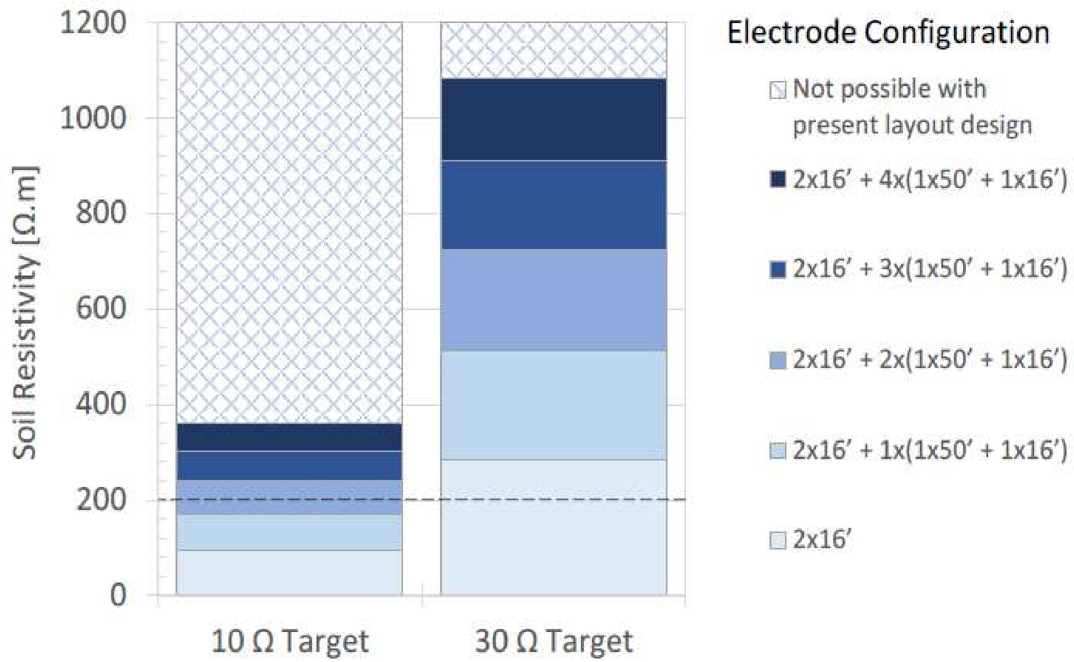

Figure 3-4
Guidance for selecting electrode configuration as a function of soil resistivity.

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Conclusion and Next Steps

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How Good Are The Models

- What we expect……………..

- But, sometimes we get this!

What We Know and Don’t Know

- We don’t know how lighting will react.
  - It’s unpredictable.
  - It’s nearly impossible to stop all lightning outages.
- We don’t know the ground resistance along the entire line early in the project.
  - The ground resistance along a line route can change sometimes from structure to structure.
  - We know obtaining 10 Ohms footing resistance everywhere is not realistic.
    - And is costly to try and hit this target.

What We Know and Don't Know

- We know the system appears to perform better than the models.
  - Other utilities have seen similar results.
    - But there can be anomalies too.
  - Plans to work with EPRI along with other utilities to fine tune models.
- We now have a better grasp of the structure design parameters and how they influence the lightning performance of the transmission structures.
  - Lattice towers and h-frame have a much lower structure surge impedance than monopole structures.
  - Taller structures & longer spans are going to have higher outage rates.
  - A lower voltage transmission lines on double circuit lines with a higher voltage line are typical going to perform worse than on a single circuit configuration.
- We know we need to invest in the technical expertise to continue to improve the lightning performance of the structure designs.
  - Experienced engineering staff is difficult to find in the current job market.
  - There is a steep learning curve for new hires out of school.
  - EPRI helped FirstEnergy fill this technical gap and gave us to the tools to perform future analyses.

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Thank You

QA

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Appendix

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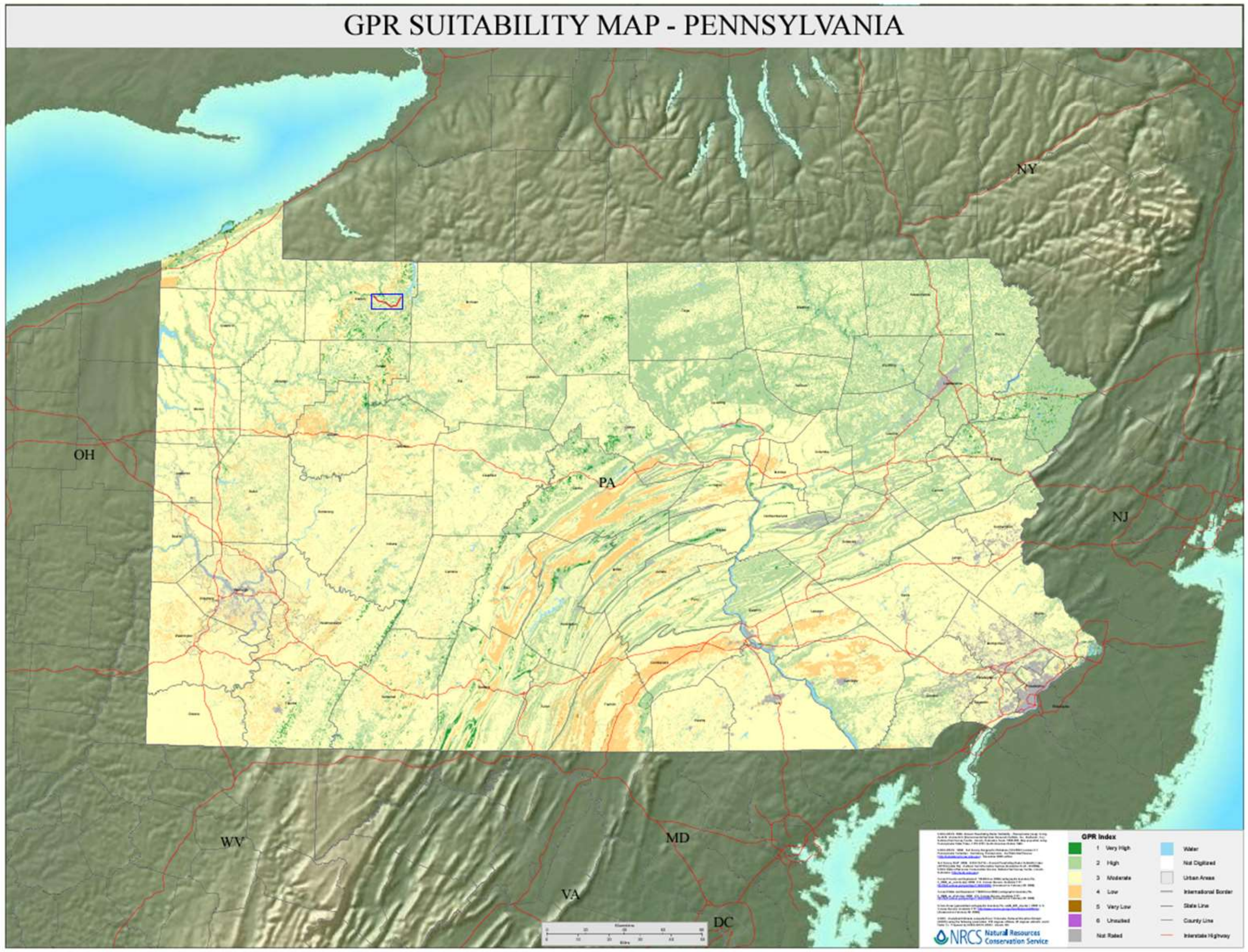
Other Tools

- Ground Penetration Radar (GPR) maps from the NRCS.
  - Available online at no cost.
  - Ground resistance tends to be inversely related to GPR suitability

GPR Index

1	Very High
2	High
3	Moderate
4	Low
5	Very Low
6	Unsuited
	Not Rated



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