How do we fix the Network Model When it doesn't match Reality?

Presented to the

69th Annual Conference for Protective Relay Engineers

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Introduction

Between 80-90% of all power system faults involve ground. Many protective relaying schemes depend on ground distance protection to accurately sense and locate ground faults on multi-terminal MV transmission and HV transmission lines.

In addition to the need of dependable ground fault detection, protective relaying must provide adequate selectivity to avoid over tripping for faults outside of its zone of protection as well as under tripping, both of which cause unintended grid operations.

Introduction

Due to continuing power system disturbances in North America, such as the major Northeast blackout of 2003, misoperations are always scrutinized.

Correct application, setting, and testing of protective devices, particularly distance relays, are now mandated by NERC/FERC with new standards now in force.

Application of distance relay settings has been a major topic inside and outside electric power utilities as well as standards making groups such as the IEEE Power Systems Relaying Committee and IEC.

It is apparent that the accuracy of our Power System grid parameters affect our network models and quality of our work in this business.

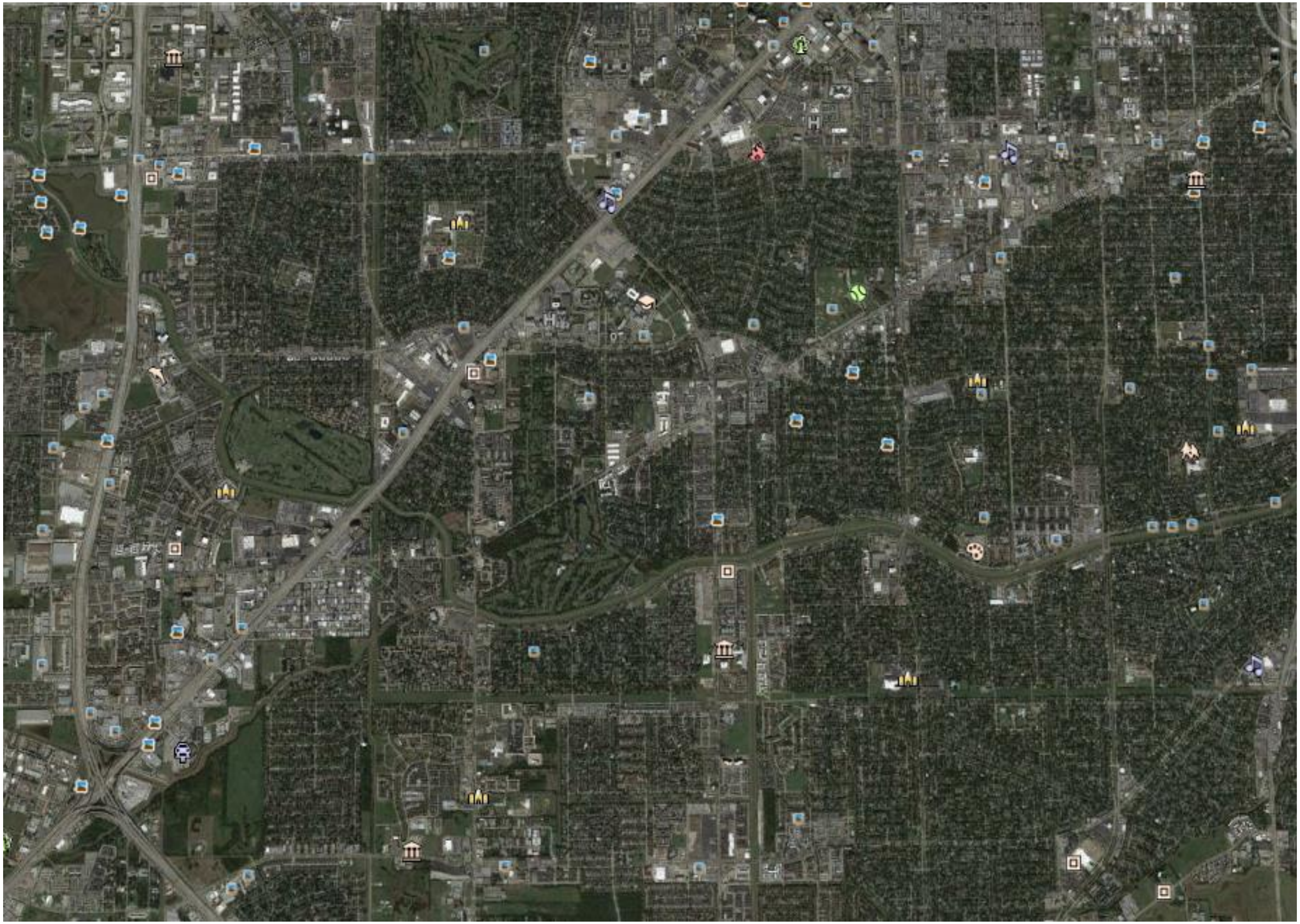
System Settings and Distance Relays

- Why do the grid parameters change?
  Growth, Expansion, Infrastructure Changes
- Ground Distance Relays (using Zone Schemes) are critical to modern power system stability and operations
- Proper line parameters and protection settings are critical for reliable and secure zone protection
- Correct K-Factors are Critical for Ground Settings so what problems can influence these settings?
- K-Factors can be derived from Measurements!

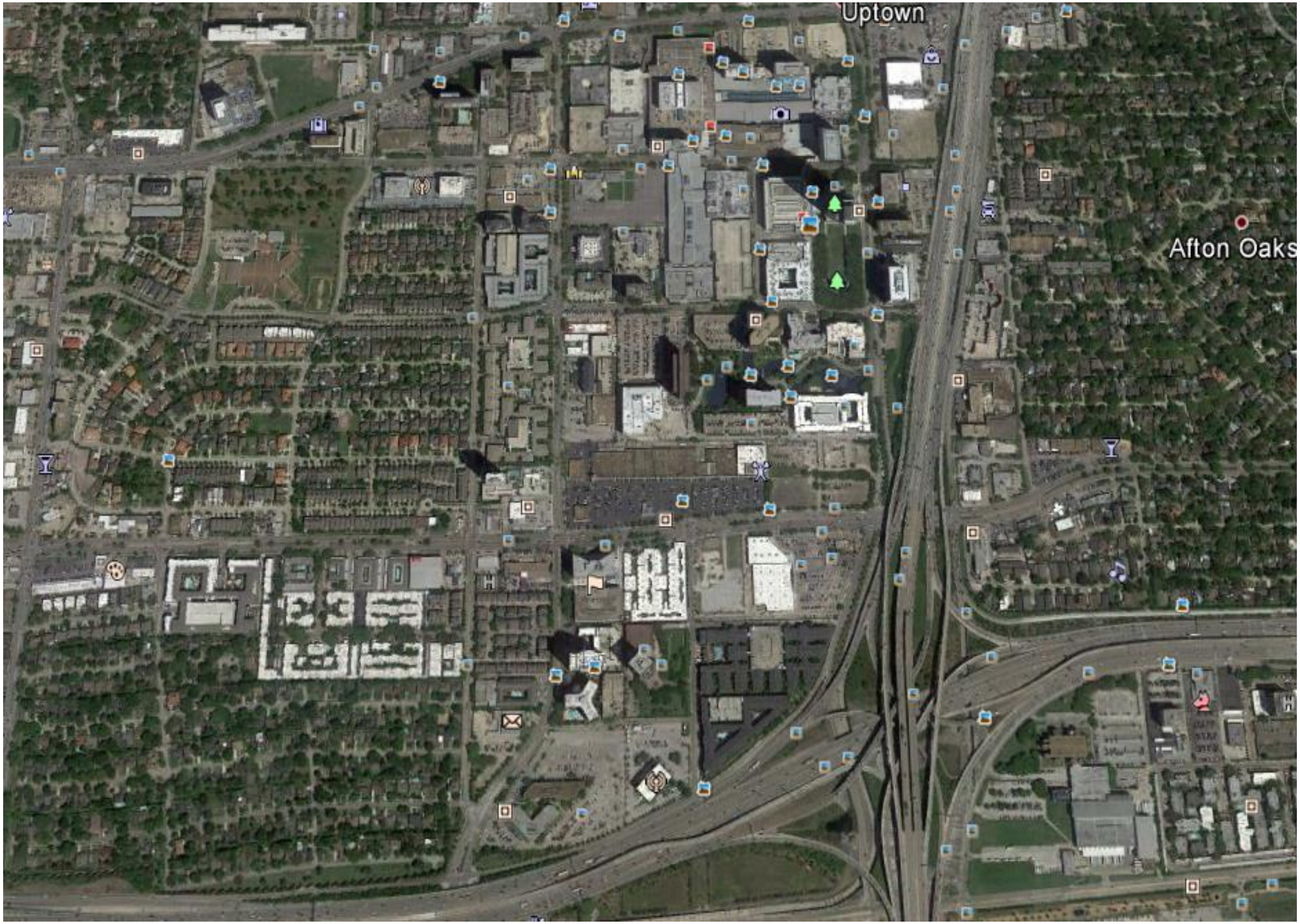
Infrastructure+Growth+Expansion

(factors in ground resistance measurement)

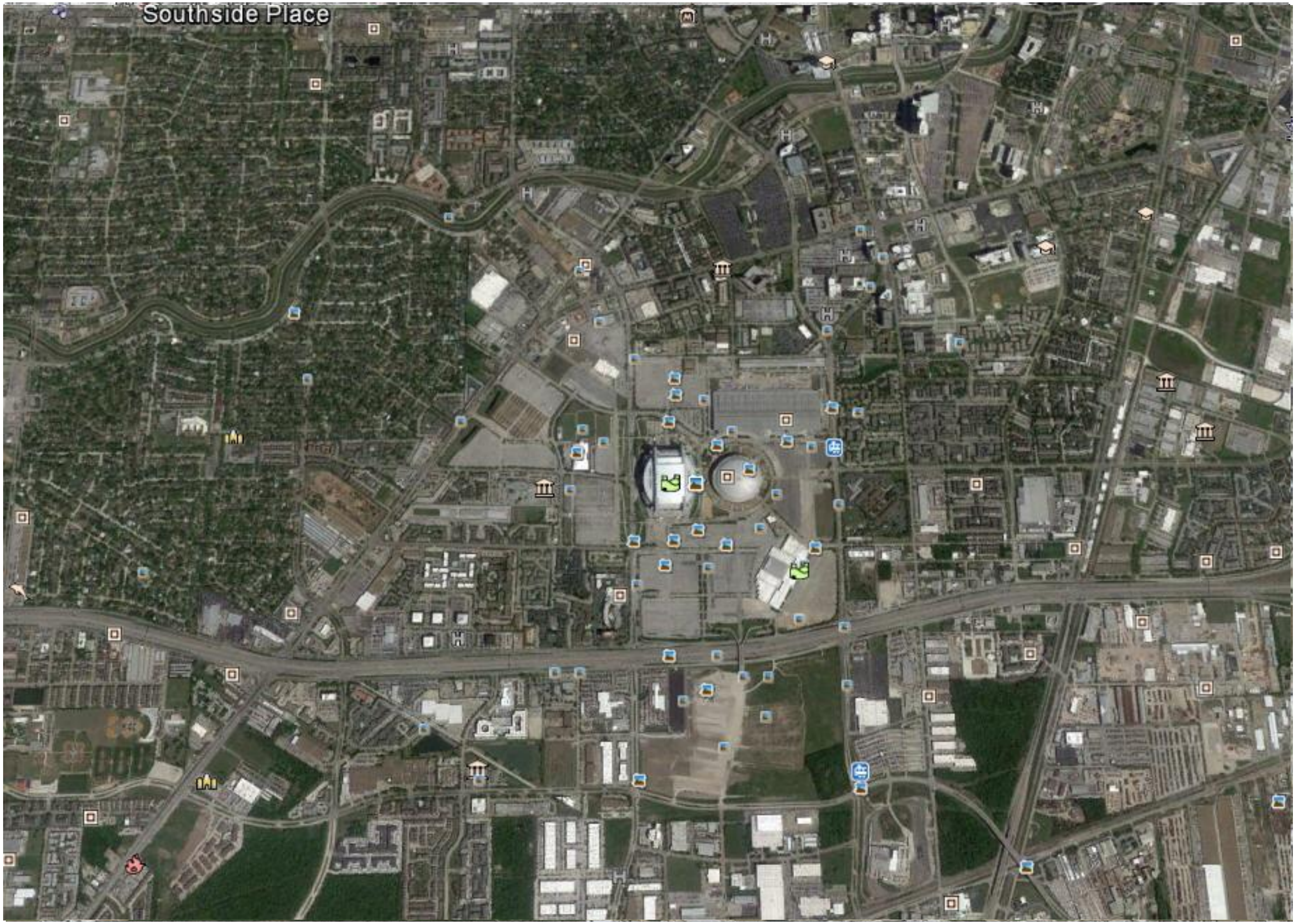
Sugarland 1950 - Today



Galleria Area 1950 - Today



South Loop 1950-Today



Ground Distance Relay

Ground Distance Relay

Although ground distance relay design, characteristics, and implementations vary, some of the typical parameters required to set a ground distance relay include the following:

> Zone impedance reach and characteristic angle
>
> Blinder positions, (resistive reaches and angles)
>
> Directional supervision limiting angle
>
> Polarizing current (3I0, I2)
>
> Supervising element (3I0)
>
> Z0/Z1 (zero-sequence compensation)
>
> Z0M/Z1 (zero-sequence mutual coupling compensation)

Ground Distance Relay

This means that determining the following parameters are key for the Ground Distance element to operate correctly.

> ZGnd Reach and Gnd Angle

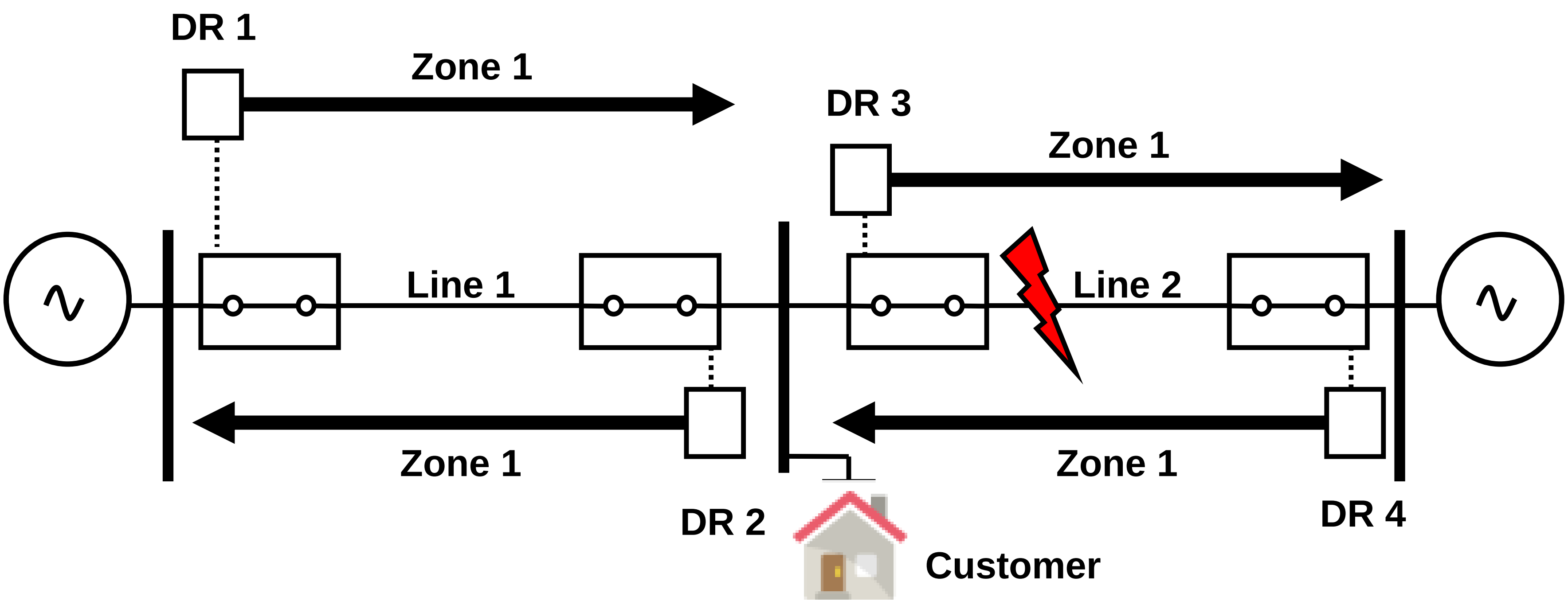
> Supervising element (3I0) and limit angle

> Z0 Zero Sequence Impedance

> Z1 Positive Sequence Impedance

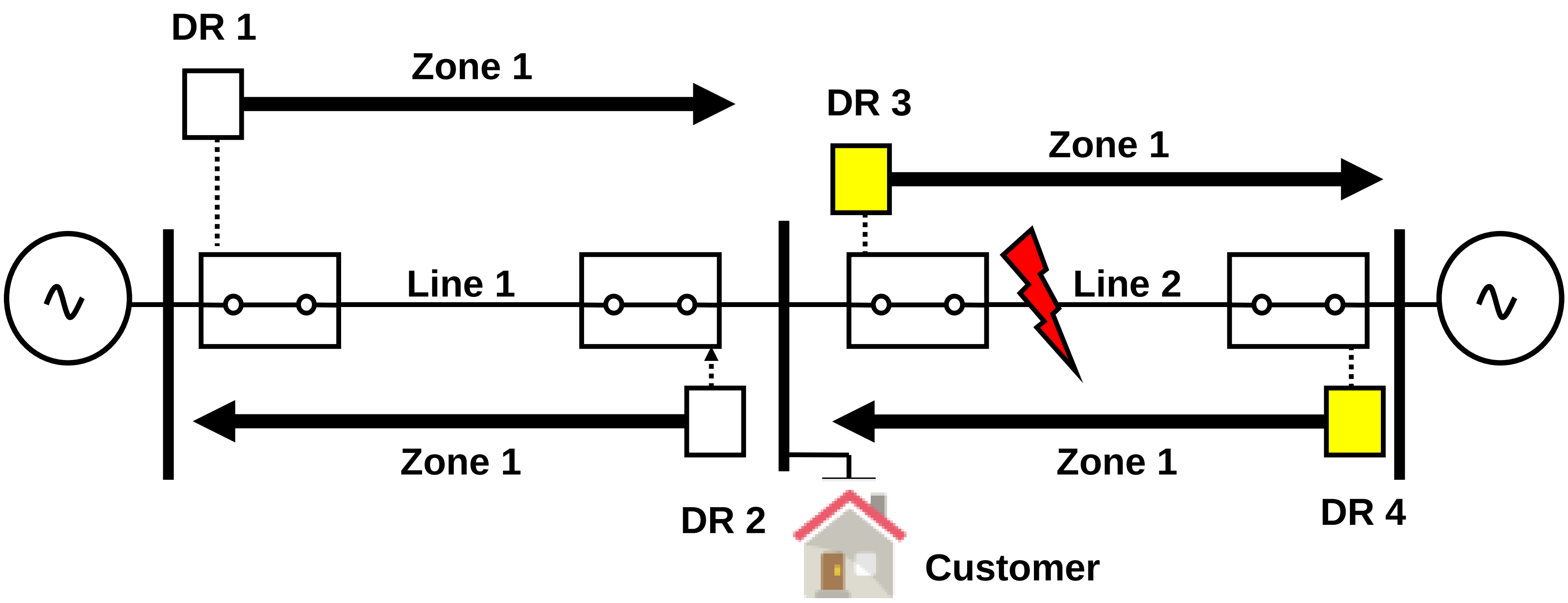
> Z0M Zero Sequence Mutual Coupling Impedance

Ground Distance Relay - Idealized



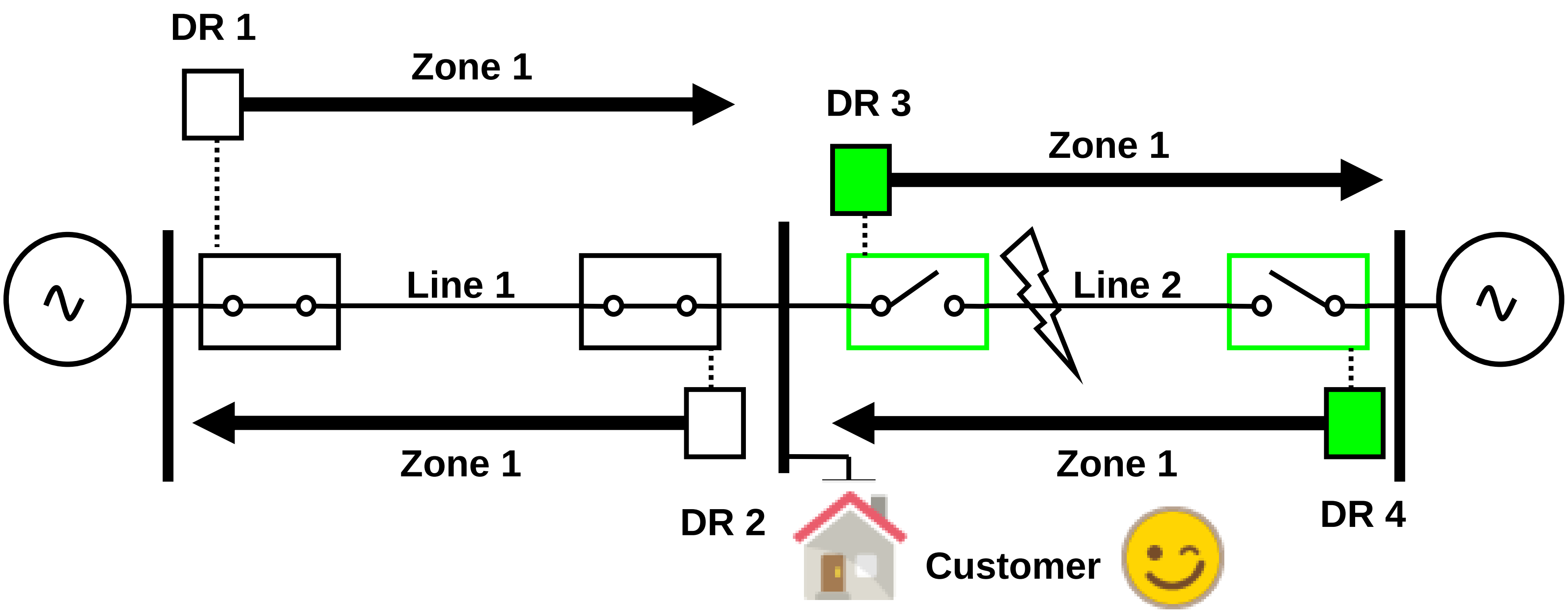
- **Each Zone covers 100% of line impedance – idealized**
- **A Phase-to-Ground Fault on Line 2, 10% of DR 3 Reach Setting**

Ground Distance Relay Zone Scheme



- DR 3 and DR 4 see the fault in Zone 1.
- DR 3 and DR 4 Trip to Clear the Fault.

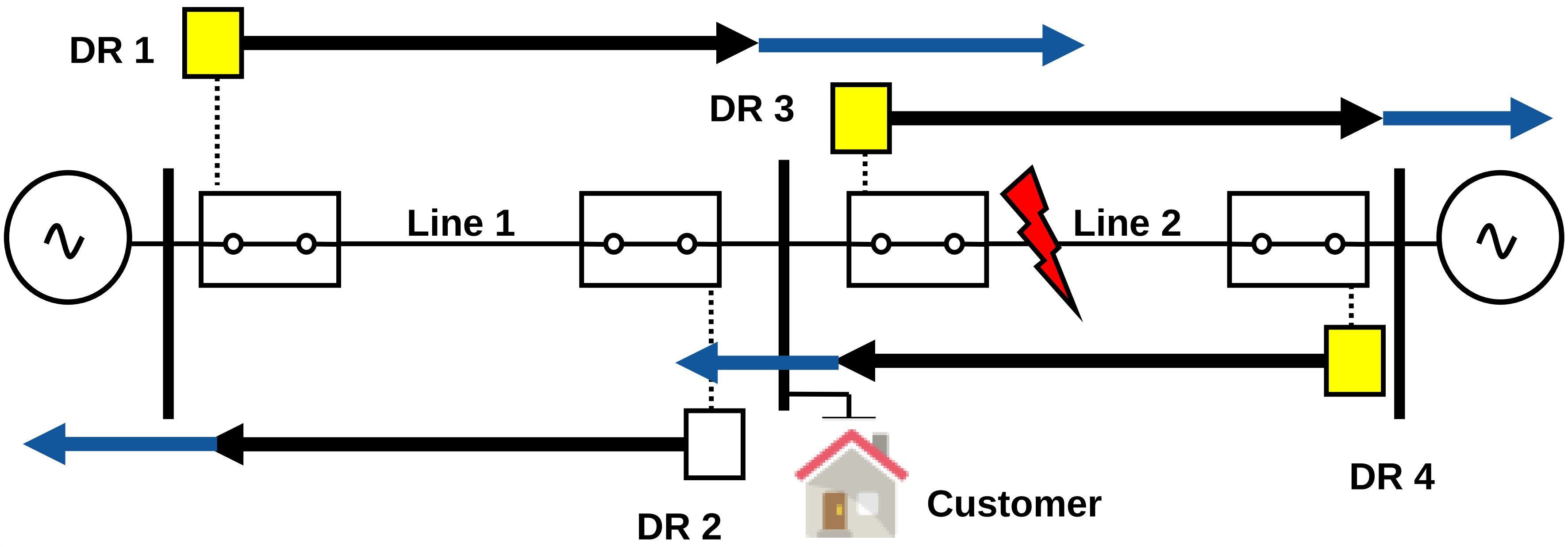
Ground Distance Relay Zone Scheme



- Fault cleared no time delay minimizing the disturbance.
- Consumer continues service via Line 1.

What if the K-Factor is in Error by + 20%?

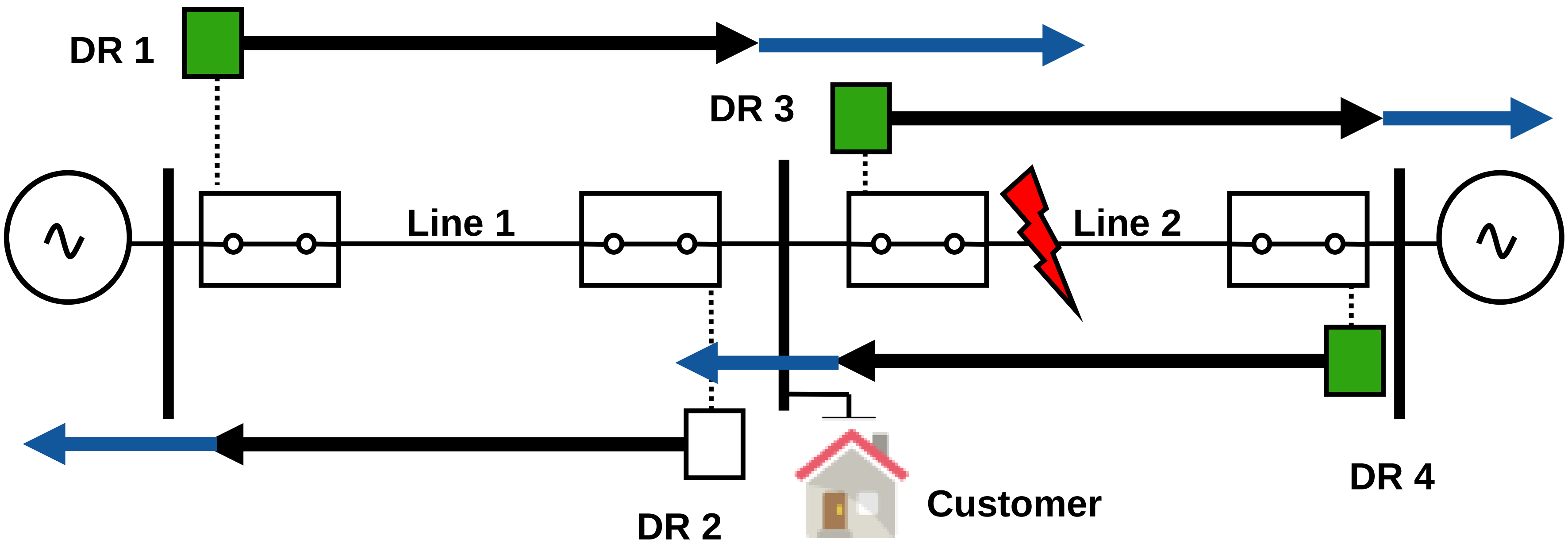
Overreach Occurs



- DR 1 also detects the Fault on Line 2.

What if the K-Factor is in Error by + 20%?

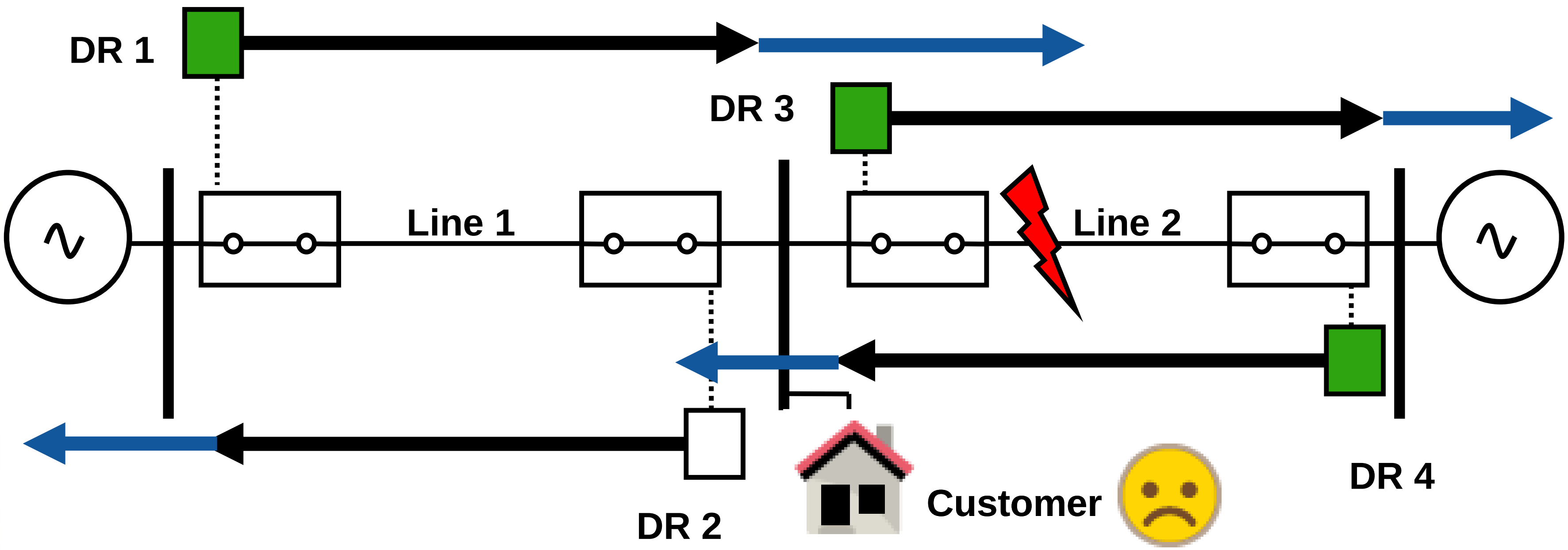
Overreach Occurs



- DR 1, 3, and 4 see the fault in Zone 1, and Trip.

What if the K-Factor is in Error by + 20%?

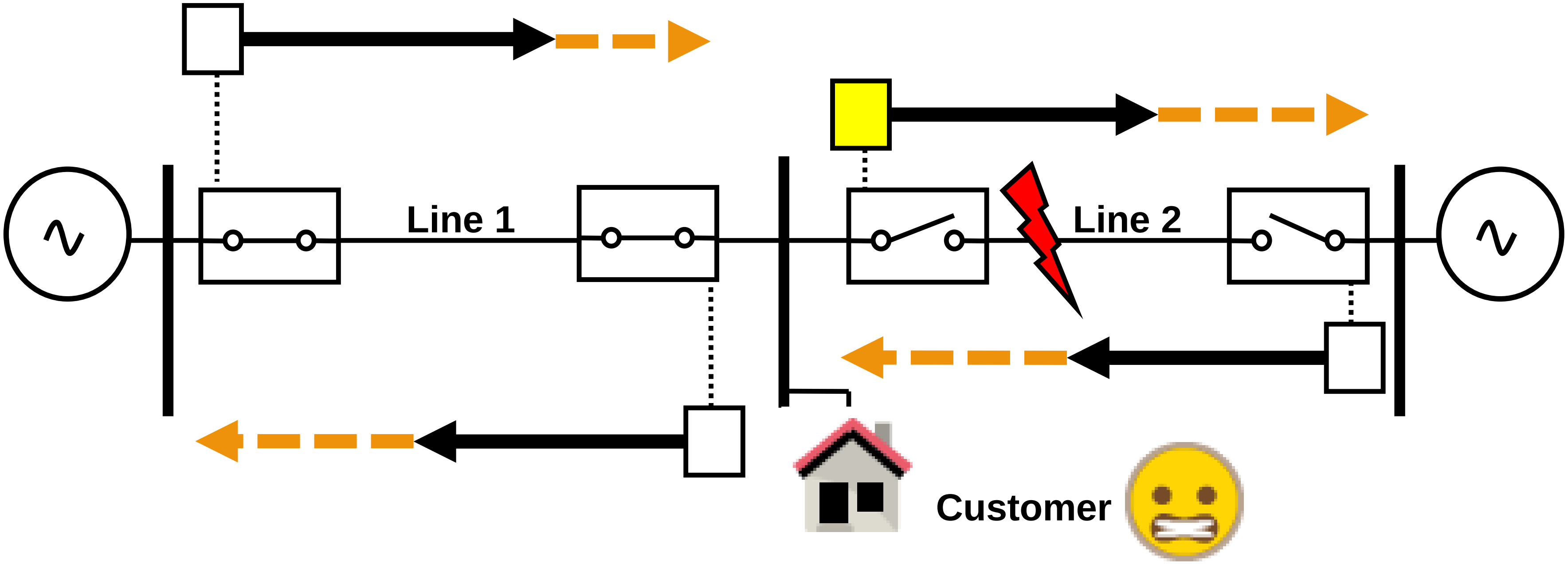
Overreach Occurs



- DR 1, 3, and 4 see the fault in Zone 1, and Trip.
- Consumer loses service as both Line 1 & 2 are isolated.

What if the K-Factor is in Error by -20%?

Under-reach Occurs



- System potentially suffers longer fault exposure.
- Potential relay coordination problems if backups don’t work.
- Consumer may experience Power Quality issues.

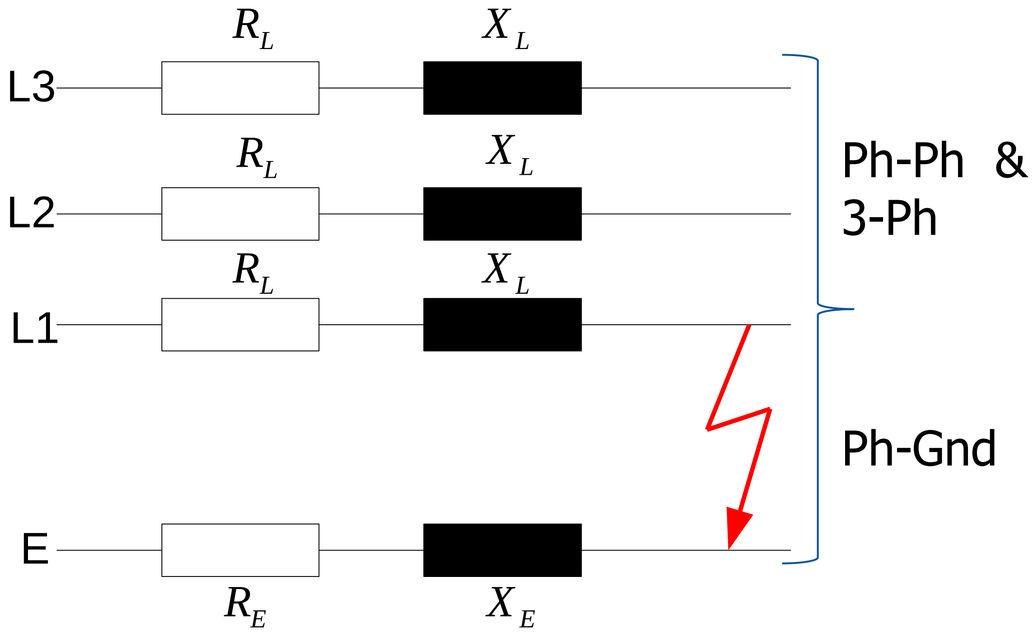
K- Factor Calculation

- **A "k- factor" is a constant of the Line**
- Ratio between Line and Earth impedance
- A critical setting of a distance relay!

$Z_L = R_L + X_L$

$Z_E = R_E + X_E$

$$\boxed{\underline{k}_L = \underline{Z}_E / \underline{Z}_L}$$



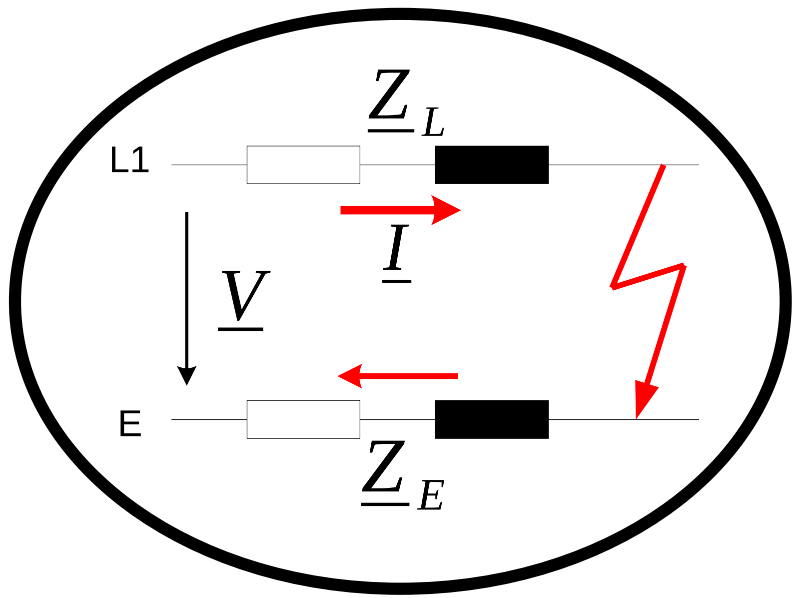
K- Factor Affects the Z_L Ground Setting

$$\underline{V} = \underline{I} \cdot (\underline{Z}_L + \underline{Z}_E)$$

$$\underline{V} = \underline{I} \cdot \left(\underline{Z}_L + \frac{\underline{Z}_E}{\underline{Z}_L} \underline{Z}_L \right)$$

$\underline{k}_L$

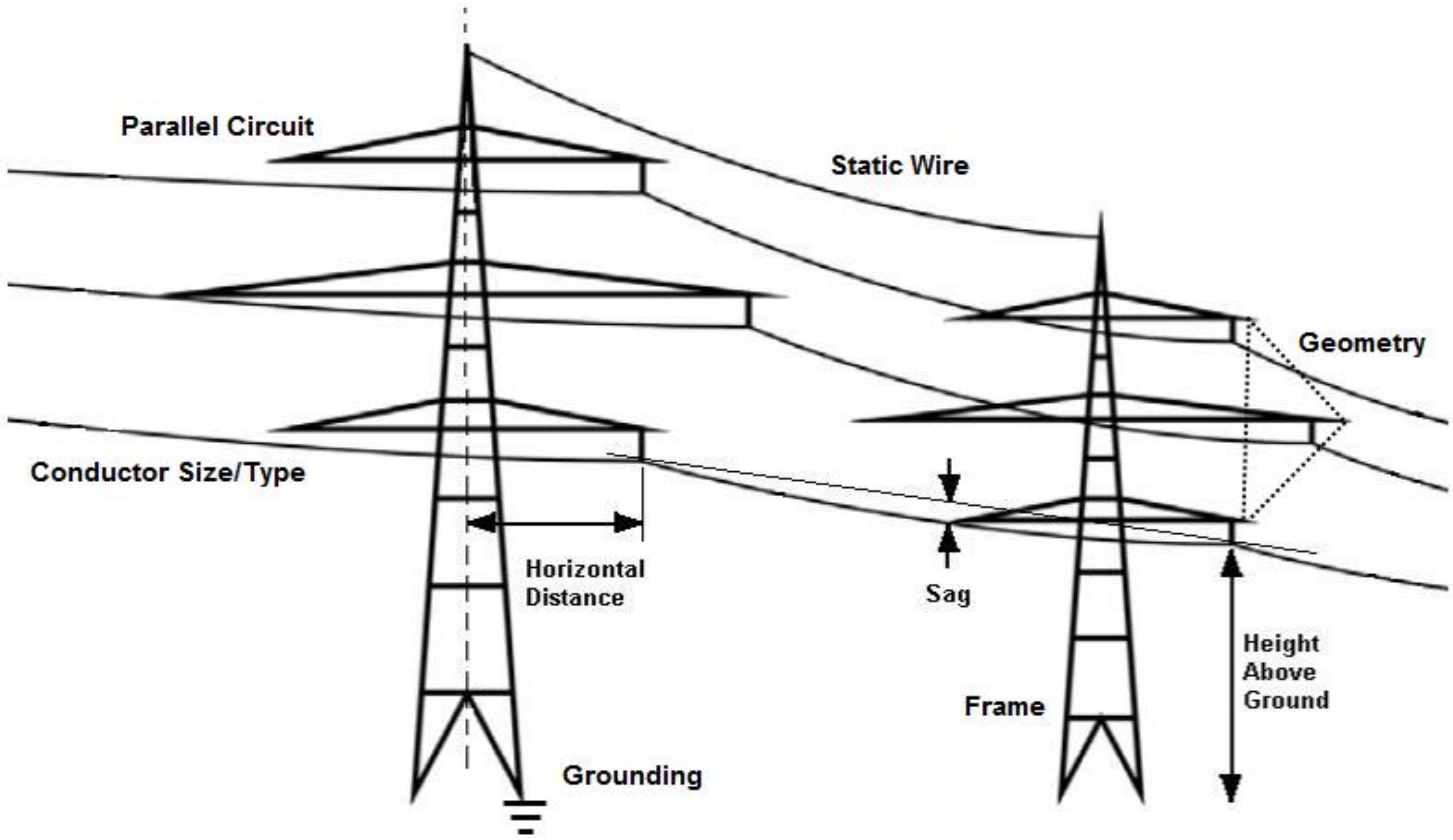
$$\underline{V} = \underline{I} \cdot (\underline{Z}_L + \underline{K}_L \underline{Z}_L)$$



$$\boxed{\underline{Z}_L = \frac{\underline{V} / \underline{I}}{1 + \boxed{\underline{K}_L}}}$$

The precision of this setting effects the accuracy of a distance relay dramatically!

Line Parameters



Determining the Line Parameters

Transmission line impedances are typically calculated by a line constants program. Line parameter calculations are prone to error, particularly in the zero-sequence impedance value of the line.

There are a large number of variables, including:

> **Soil Resistivity** values (10Ωm-100Ωm, etc.) **?**

> **Line Geometry** *(typically known)*

> **Construction** *(typically known)*

> **Materials** *(typically known)*

> Tower Grounding Method *(typically known, quality ??)*

Determining the Line Parameters

Soil Resistivity

> The soil resistivity value is subject to great variation, due to moisture, temperature and chemical content. Typical values are:

> Usual values: from 10 up to 1000 (Ω-m)

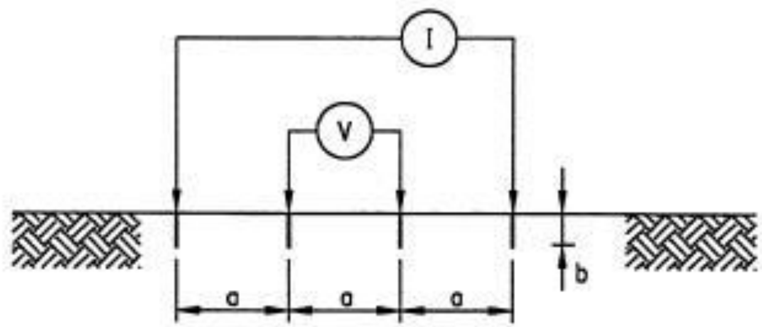
> Exceptional values: from 1 up to 10000 (Ω-m)

Two methods are typically used for measuring:

Wenner method or the Schlumberger method

Determining Soil Resistivity

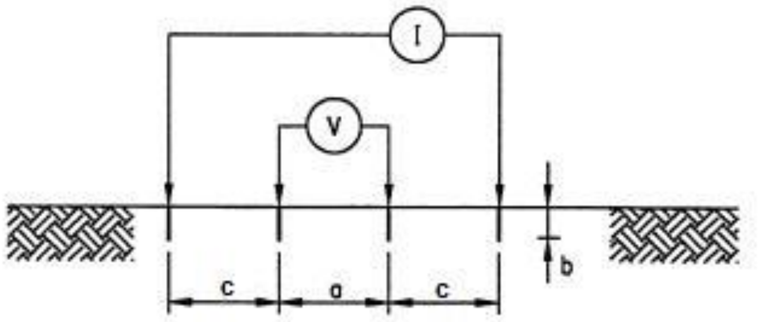
Wenner method



$$\rho_E = \frac{4 \cdot \pi \cdot a \cdot R_W}{1 + \frac{2 \cdot a}{\sqrt{a^2 + 4 \cdot b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

R_W = Wenner resistance as "V/I"

Schlumberger method



$$\rho_E = \pi \frac{c \cdot (c + a)}{a} R_S$$

R_S = Schlumberger resistance as "V/I"

ρ_E = measured apparent soil resistivity (Ωm)
a = electrode spacing (m)
b = depth of the electrodes (m)
c = electrode spacing (m)

Limiting Factors / Other Considerations

Depth of the electrode is key to both method’s accuracy.

The soil resistivity measurements will be affected by existing nearby grounded electrodes. *<u>Buried conductive objects in contact with the soil can invalidate readings</u> made by these methods* if they are close enough to alter the test current flow pattern. *<u>This is particularly true for large or long parallel objects</u>*.

Because of the variability of soil resistivity, IEEE/IEC standards recommend that the seasonal variation in resistivity be accounted for in transmission system design. When there is no other available information, in cold regions, a “winter” scaling factor of 5 to 6 times the "summer" resistivity value should be adequate.

Utility Practice for Soil Resistivity

Utility's would typically perform soil resistvity measurements as spot checks during the site survey of transmission right of ways. (ROW)

These were performed about every 10-20 miles of ROW surveyed and recorded on the platen.

These values would be averaged over the ROW length and then converted to Ohms/mile for use in the line constants.

Soil resistivity measurements declined starting in the early 1990's when utility growth exceed their resources available or no new ROW's were made due to limits or restrictions.

Utilities then began to use data from USGS, FCC, and even USDA.

Utility Source for Soil Resistivity

Example USDA Map used:

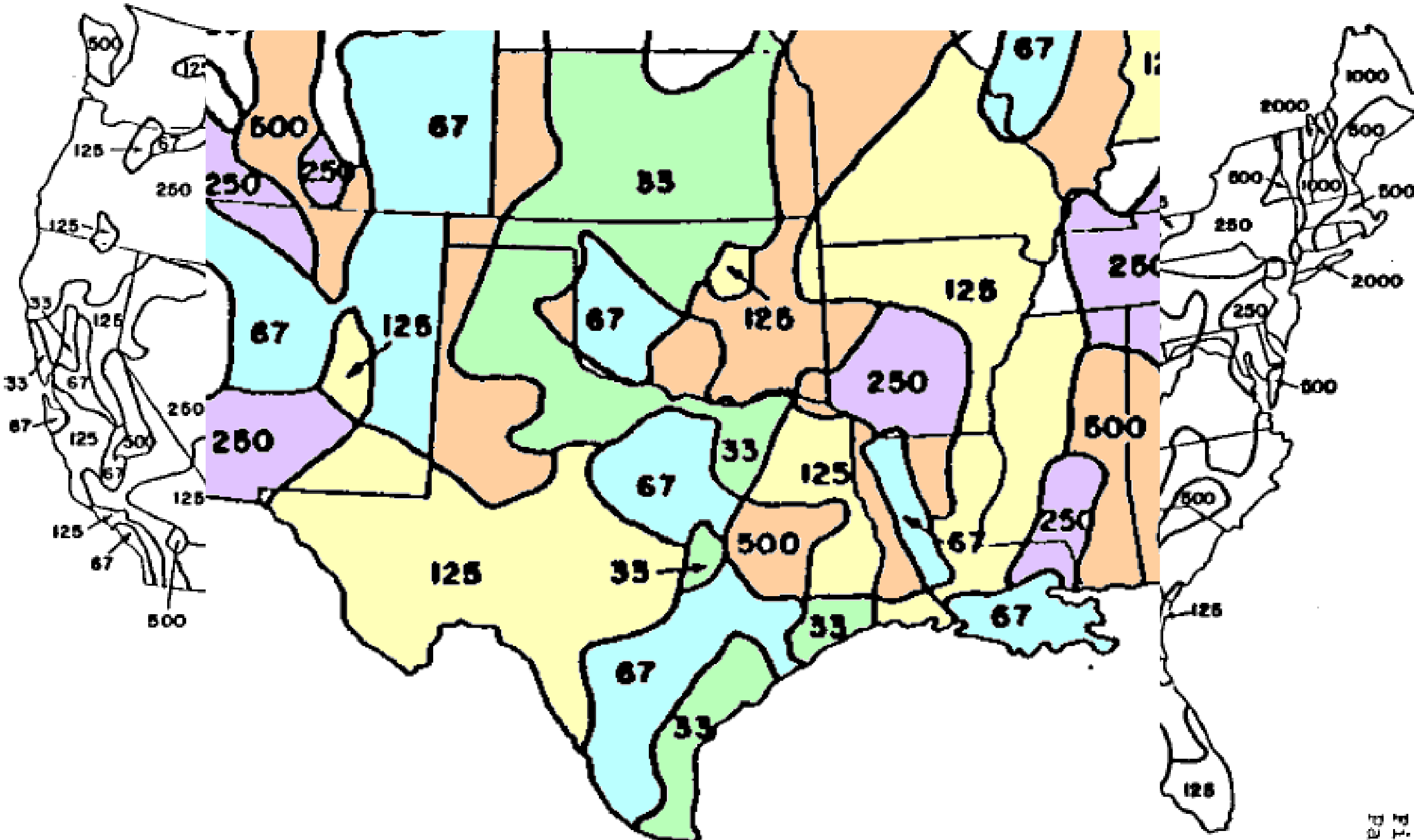


FIGURE 2

Estimated Average Earth Resistivity in U.S. (ohm·meters)

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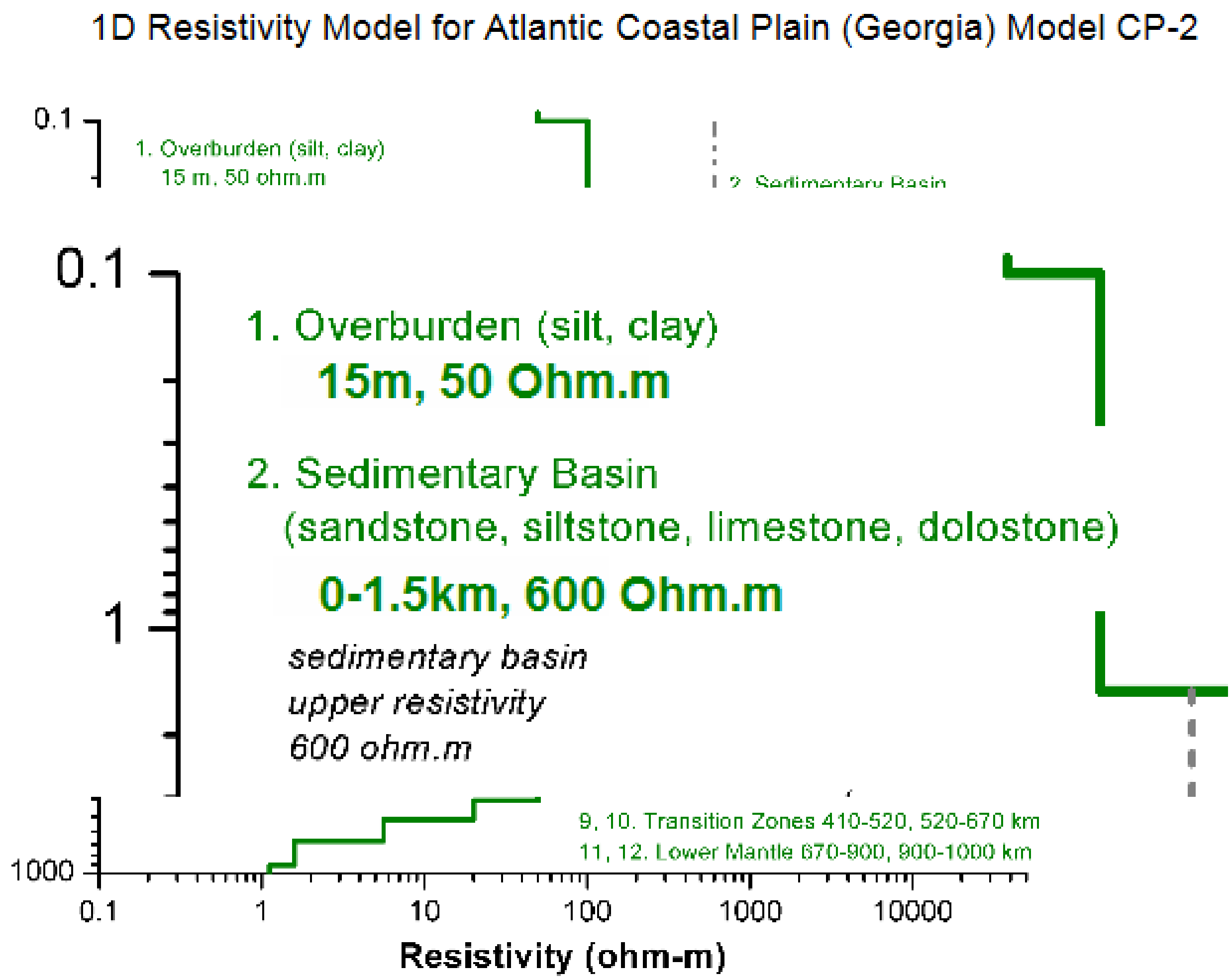
Utility Source for Soil Resistivity

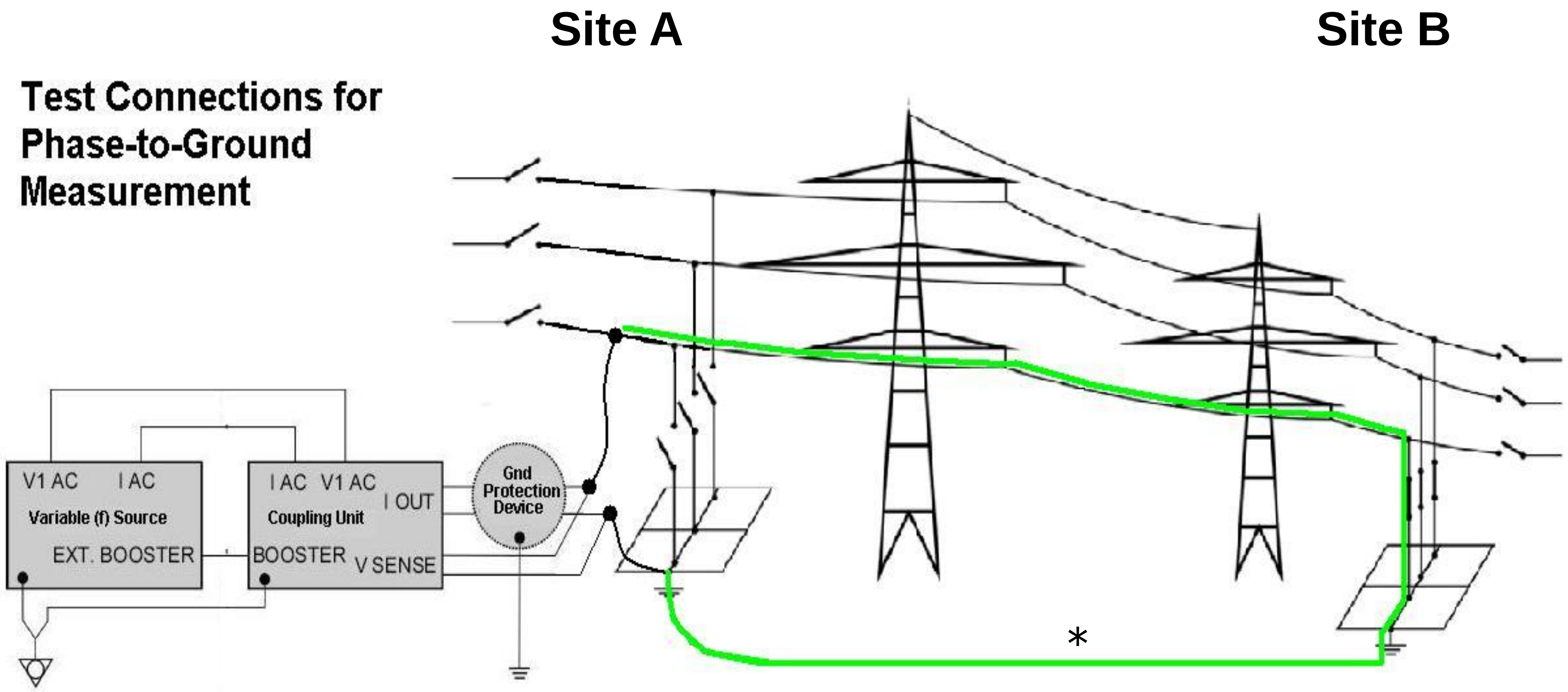
Example USGS Data used:



Model Suspect?

(Direct Site to Site Measurement)

Measuring Line Impedance



* Inclusive of all infrastructure and soil composition

Measuring Line Impedance

- Overall, seven measurements per system are made, 3 for each L-L and L-N loops and one 3L-N.
- Currents range from 10-100A depending on line length.
- Off frequency injection allows smaller currents without interference from system frequency.
- Selective digital filter measuring ensures high accuracy.
- Redundancy in measurements allow reliability crosschecks and calculation of individual k-factors for each phase.
- Results are post-processed in Excel for quick calculations and flexible reporting templates.

Example Test Results

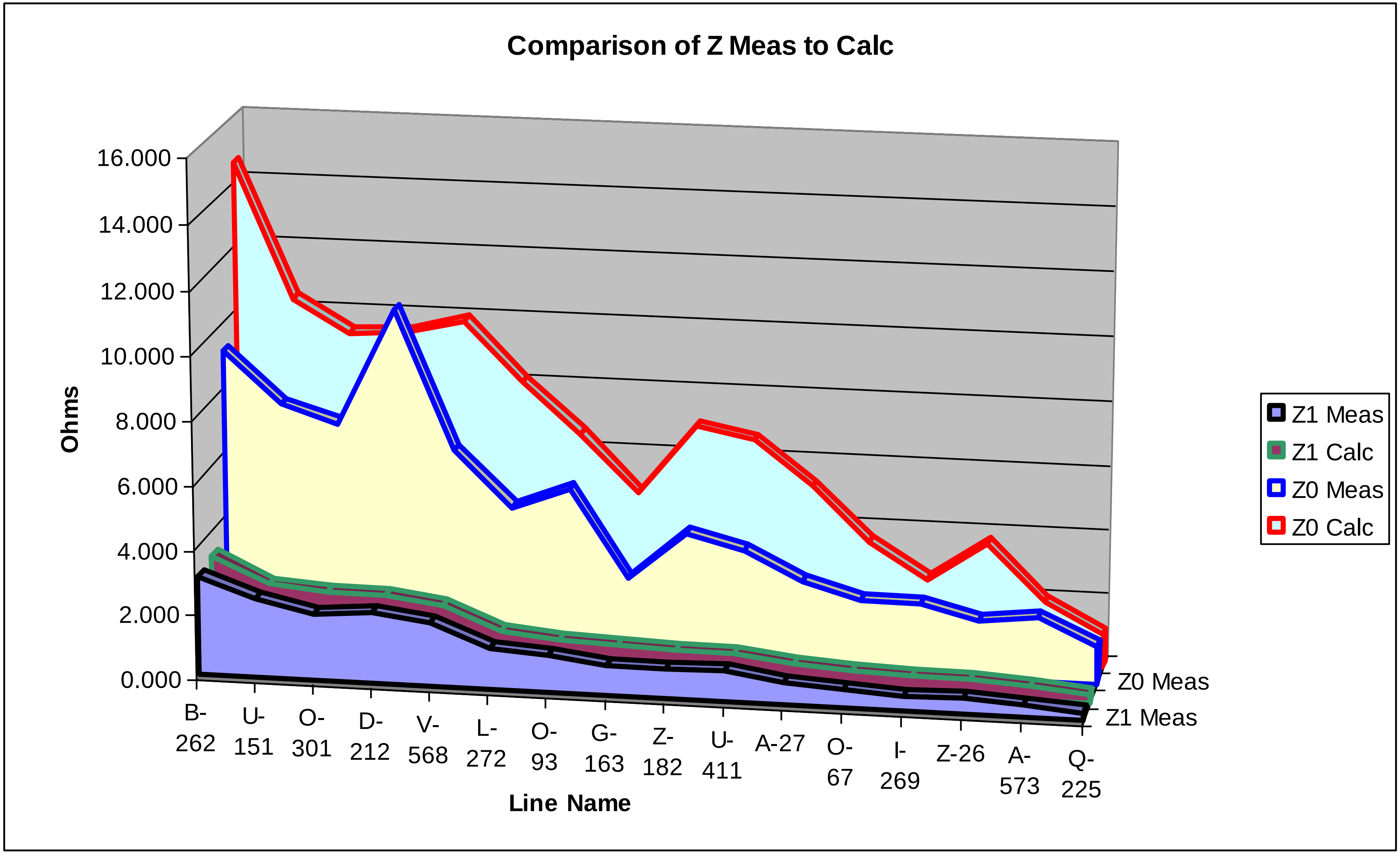
Individual Loop Measurements:	R [Ω]	X [Ω]	Z [Ω]	Phi (°)
L1-L2: $Z_{L1} + Z_{L2}$	0.850	3.781	3.875	77.32°
L2-L3: $Z_{L2} + Z_{L3}$	0.865	3.785	3.883	77.12°
L3-L1: $Z_{L3} + Z_{L1}$	0.864	3.698	3.797	76.85°
L1-E: $Z_{L1} + Z_E$	0.590	2.673	2.737	77.54°
L2-E: $Z_{L2} + Z_E$	0.603	2.557	2.627	76.73°
L3-E: $Z_{L3} + Z_E$	0.625	2.564	2.639	76.31°
L1L2L3-E: $Z_{L1}//Z_{L2}//Z_{L3} + Z_E$	0.321	1.346	1.383	76.60°
Impedance Results:	**R [Ω]**	**X [Ω]**	**Z [Ω]**	**Phi (°)**
Positive sequence impedance Z_1	0.430	1.877	1.926	77.10°
Zero sequence impedance Z_0	0.962	4.037	4.150	76.60°
Ground Compensation by K-Factor Type			**[1]**	
$k_L = Z_E / Z_L$			0.385	-0.93°
R_E / R_L and X_E / X_L			0.412	0.384
$k_0 = Z_0 / Z_1$			2.155	-0.50°

Example of Impedance Measurements & Calculations

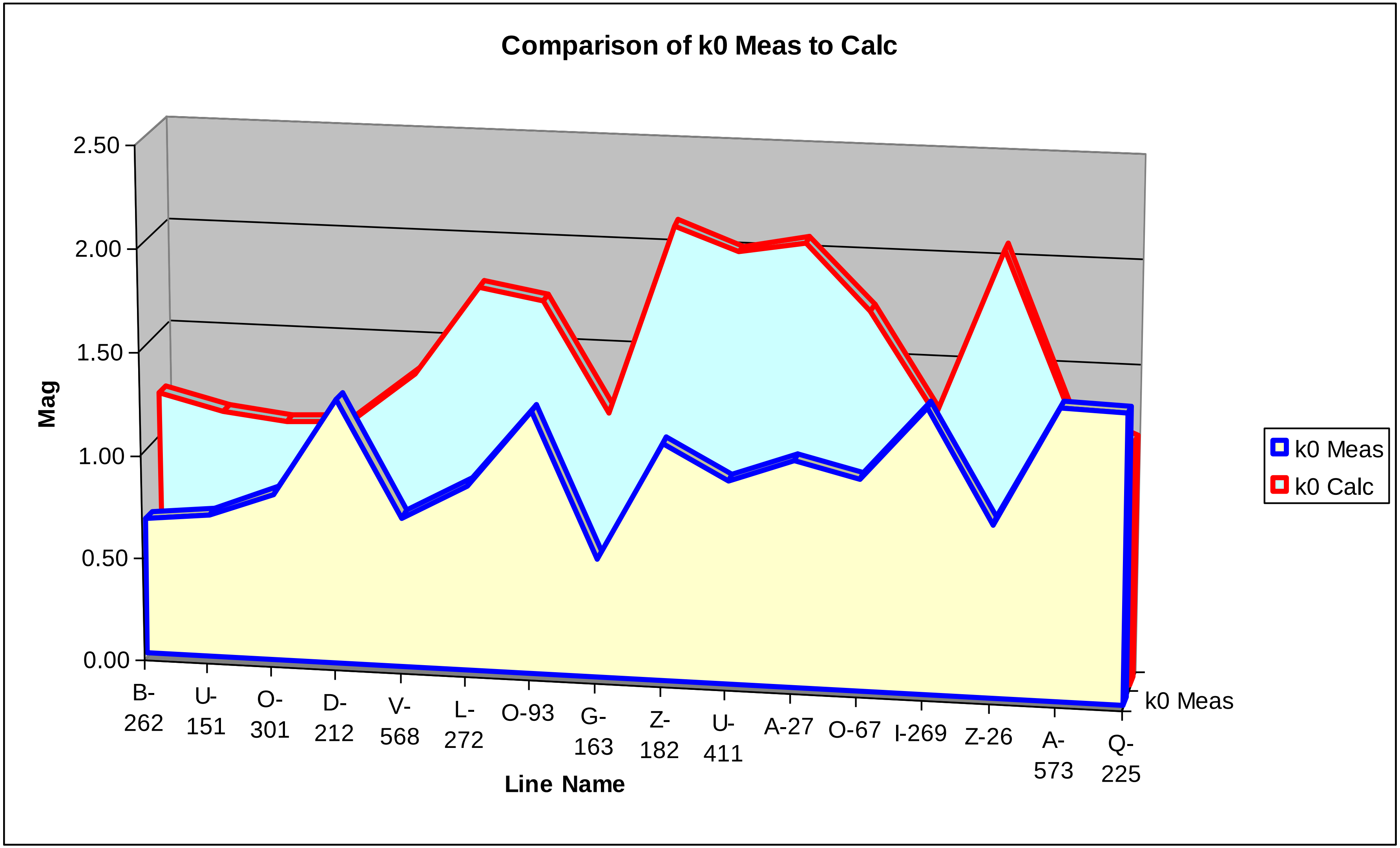
1st US Utility Experience

- Utility‘s Sub-transmission system experienced nusiance trips
- Distance relay settings were suspect
- Opted for actual measurements to determine settings
- Out of 16 lines measured, 15 had higher zero sequence magnitudes than previously calculated
- Average difference was 51% between Calculated vs. Measured, with range of 10% to 107%
- Positive sequence Calculated vs. Measured within 3.5%
- Overall, K-Factor error range was -15% to +147%
- Program underway to measure all remaining Sub-transmission

Utility Results 69kV System



Utility Results 69kV System



Utility Conclusions

> Right of Way: is there a new water pipe, gas line, railway or other parallel/crossing infrastructure?

> Parallel line influences

> Measurements showed definite differences between calculated and measured impedances

> Measurements were simple to perform and based on comparisons of the positive sequence, reliable

> Costs are comparable to total modeling costs but of less overall effort

> New relay settings have been implemented awaiting Murphy to test them (Update: no misoperations todate)

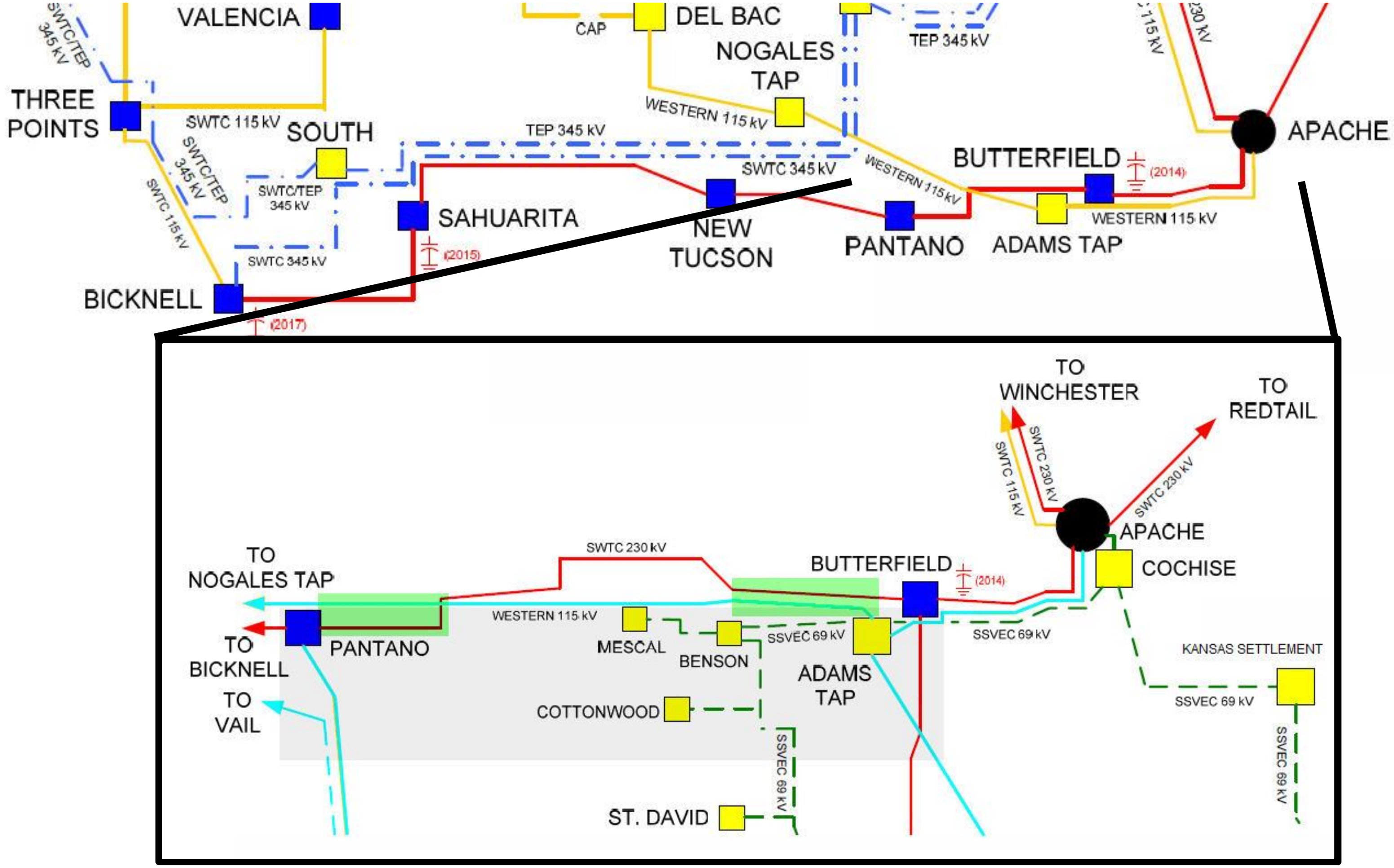
> Definitely recommended for new construction

Case Study #1 – Overhead Line

- Utility had experienced some nuisance trips after upgrading some of their 230kV lines and suspected incorrect ground settings
- One line segment was available, part of a overall 230kV corridor. They decided to try and measure the circuit parameters
- Tests were conducted at the end of the line segment upgrade.The process was completed within a 3 hour window
- The line was put into service a few days later
- Test results were peer reviewed as valid

Case Study #1 – Overhead Line

Case Study #1 – Overhead Line



Case Study #1 – Overhead Line

ROW, Tower Construction, Surrounding facilities, Topology contributes to earth ground return paths, so does following a major freeway and rail.

Case Study #1 – Overhead Line Results

Temperature Correction:	
Material	Al
Measurement Temperature	23°C
Reference Temperature	25°C
Temperature Correction Factor	1.008

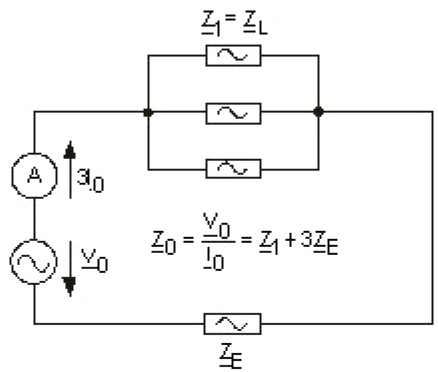
Measurements:	R [Ω]	X [Ω]	Z [Ω]	Phi (°)
L1-L2: $Z_{L1} + Z_{L2}$	6.959	45.570	46.098	81.32°
L2-L3: $Z_{L2} + Z_{L3}$	6.965	45.531	46.061	81.30°
L3-L1: $Z_{L3} + Z_{L1}$	7.046	50.484	50.973	82.05°
L1-E: $Z_{L1} + Z_E$	6.739	32.233	32.930	78.19°
L2-E: $Z_{L2} + Z_E$	6.904	32.352	33.080	77.95°
L3-E: $Z_{L3} + Z_E$	6.780	33.444	34.124	78.54°
L1L2L3-E: $Z_{L1}//Z_{L2}//Z_{L3} + Z_E$	4.479	16.936	17.519	75.19°
Intermediate Results				
Z_{L1}	3.519	25.261	25.505	82.07°
Z_{L2}	3.439	20.309	20.598	80.39°
Z_{L3}	3.526	25.222	25.468	82.04°
Z_E from Measurement L1-E	3.220	6.971	7.679	65.21°
Z_E from Measurement L2-E	3.465	12.043	12.532	73.95°
Z_E from Measurement L3-E	3.254	8.221	8.842	68.41°
Z_0 from Measurement L1-E	13.179	46.176	48.020	74.07°
Z_0 from Measurement L2-E	13.834	56.438	58.109	76.23°
Z_0 from Measurement L3-E	13.288	49.887	51.626	75.08°
Line impedance Z_L	3.495	23.598	23.855	81.58°
Ground impedance Z_E	3.314	9.070	9.657	69.93°

Impedance results:	R [Ω]	X [Ω]	Z [Ω]	Phi (°)
Positive sequence impedance Z_1	3.495	23.598	23.855	81.58°
Zero sequence impedance Z_0	13.437	50.809	52.556	75.19°

$$\frac{R_E}{R_L}, \frac{X_E}{X_L}$$

$$k_L = \frac{\underline{Z}_E}{\underline{Z}_L} = \frac{1}{3}\left[\frac{\underline{Z}_0}{\underline{Z}_1} - 1\right]$$

$$\frac{\underline{Z}_0}{\underline{Z}_1}$$



Case Study #1 – Overhead Line Results

$k_L = Z_E / Z_L$				
			k_L [1]	Phi (°)
Residual Compensation Factor			0.405	-11.65°
Calculated Values:				
	R [Ω]	X [Ω]	Z [Ω]	Phi (°)
Positive sequence impedance Z_1	4.048	24.411	24.744	80.58°
Error	15.82%	3.45%	3.73%	-0.99°
Zero sequence impedance Z_0	19.950	71.950	74.665	74.50°
Error	48.47%	41.61%	42.07%	-0.68°
Residual Compensation Factor			0.675	-9.08°
Error			66.81%	2.57°

kL > +66% Error

$k_0 = Z_0 / Z_1$				
			k_0 [1]	Phi (°)
Residual Compensation Factor			2.203	-6.39°
Calculated Values:				
	R [Ω]	X [Ω]	Z [Ω]	Phi (°)
Positive sequence impedance Z_1	4.048	24.411	24.744	80.58°
Error	15.82%	3.45%	3.73%	-0.99°
Zero sequence impedance Z_0	19.950	71.950	74.665	74.50°
Error	48.47%	41.61%	42.07%	-0.68°
Residual Compensation Factor			3.017	-6.08°
Error			36.96%	0.31°

k0 > +36% Error

Case Study # 2 – U.G. Line

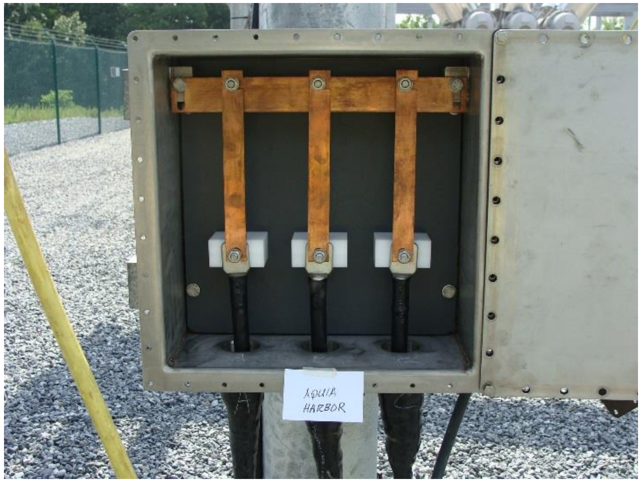
- Utility wanted to measure the parameters of a new 230kV UG Cable that had a double conductor per phase
- The UG line is 5.8 miles of 2x3500k cmil Cu XLPE cable
- There are 16 splices in the length / single bonded sheath with a 3-phase ground box at each splice connected to a dual 4/0 ground conductor EtoE.
- Calculations showed an expected Z1 of 1ohm@85deg and a Z0 of 2.76 ohm@74deg
- The test results were peer reviewed and validated

Case Study # 2 – U.G. Line

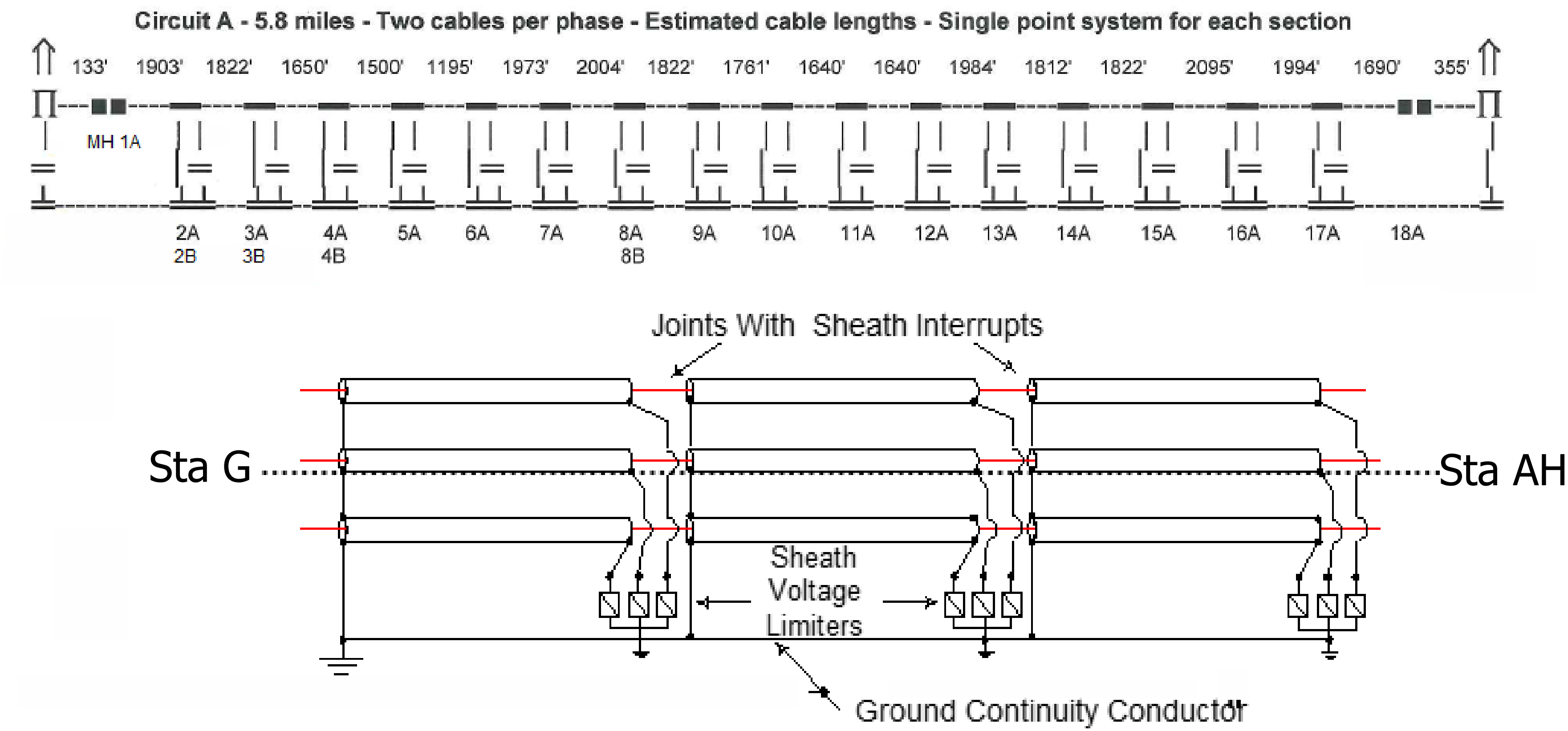
New installation as shown, easy access to all apparatus

Case Study # 2 – U.G. Line

Cable terminations to OH Bus, (1 set) / Arrestor / Ground Box



Case Study # 2 – U.G. Line



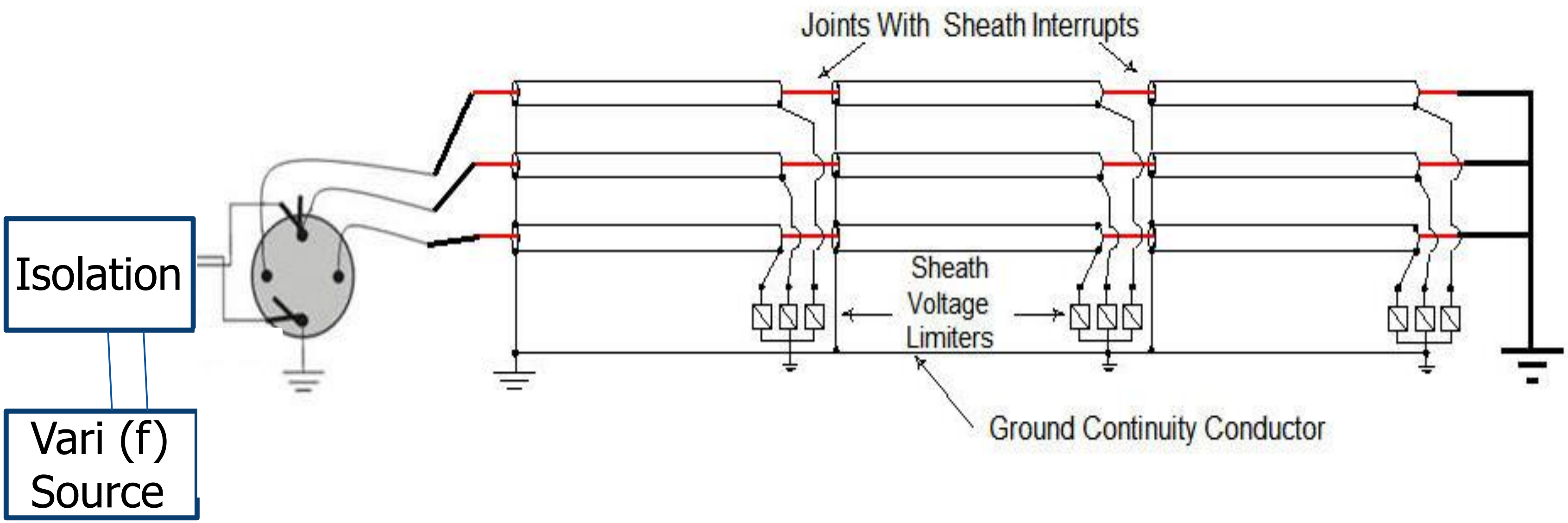
Construction¶

1)·Sheath·is·directly·grounded·

2)·Sheath·is·connected·to·Sheath·Voltage·Limiters

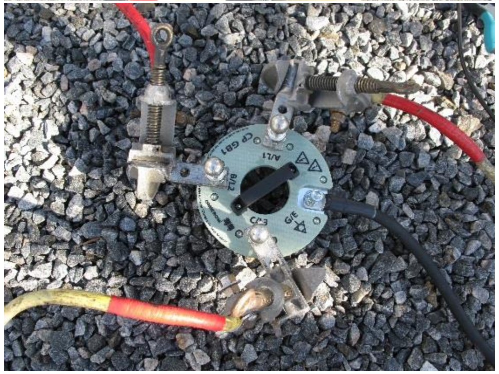
Case Study # 2 – U.G. Line

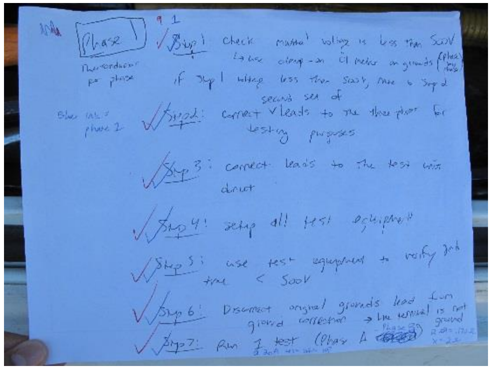
Test Setup



Case Study # 2 – U.G. Line

Connections / Verify Safety Grounds & Switches

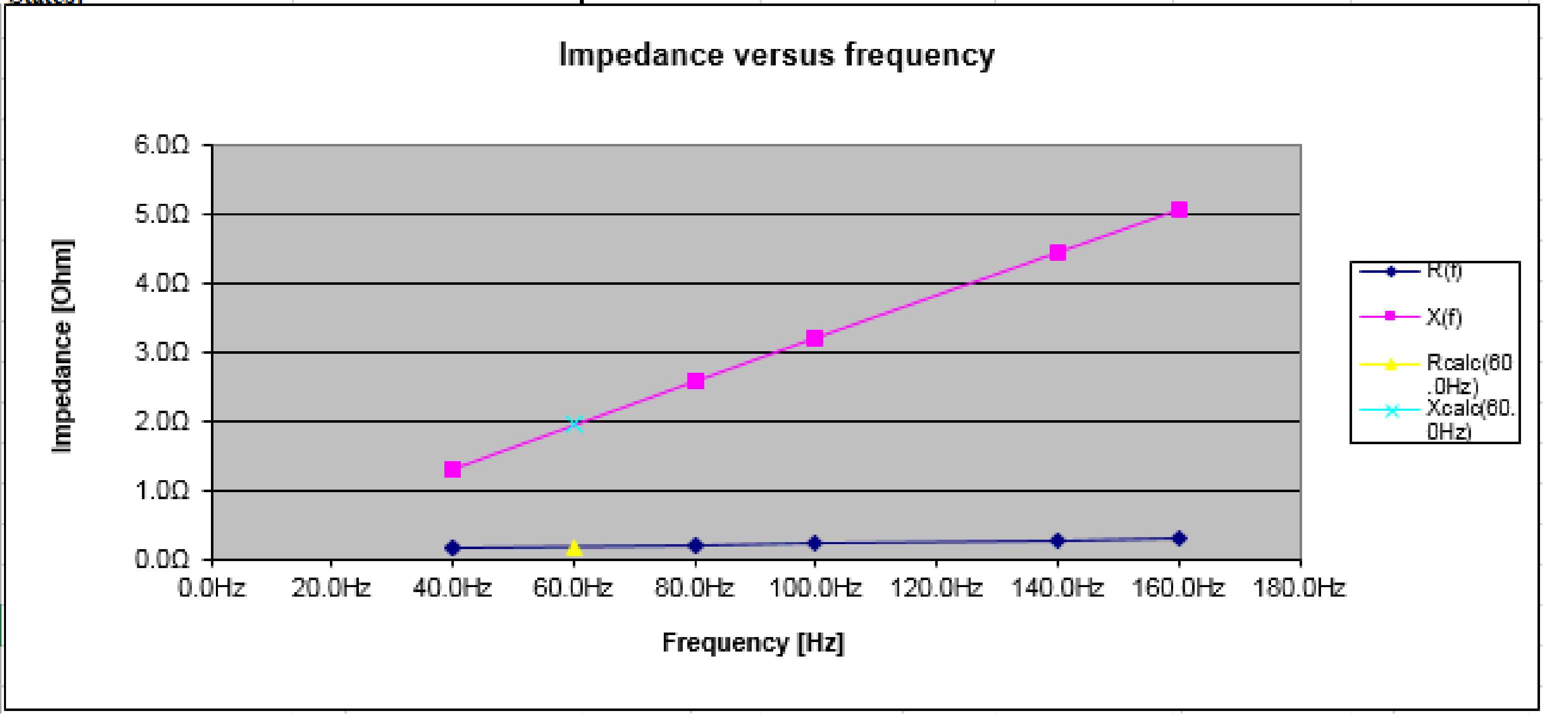




Case Study # 2 – U.G. Line

Measurement Results L1-L2

States:

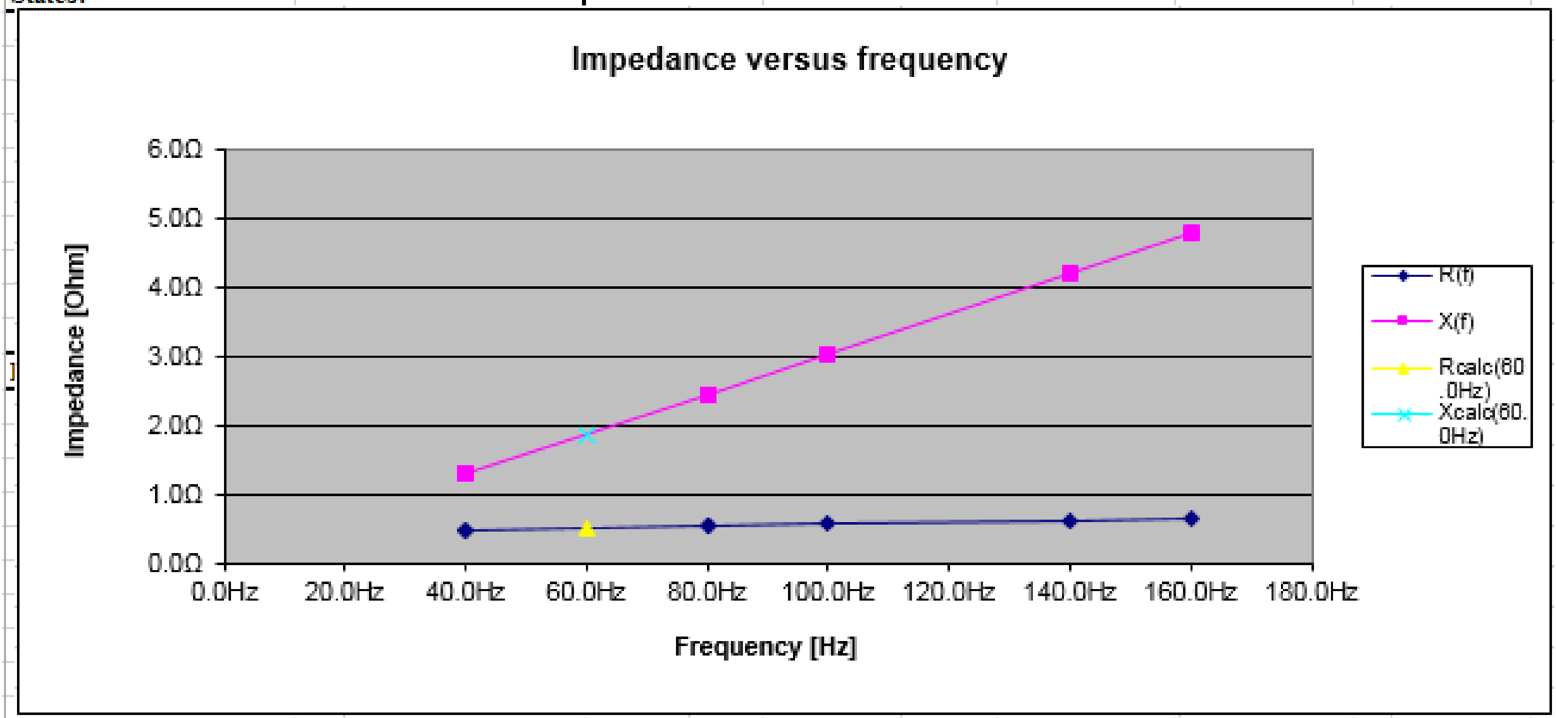


Average Calculation:	**Uncorrected:**		60.0 Hz	0.171 Ohm	1.935 Ohm
	Corrected:		60.0 Hz	0.171 Ohm	1.935 Ohm

Case Study # 2 – U.G. Line

Measurement Results L1-E

States:



Average Calculation:		**Uncorrected:**		60.0 Hz	0.505 Ohm	1.858 Ohm
		Corrected:		60.0 Hz	0.505 Ohm	1.858 Ohm

Case Study # 2 – U.G. Line

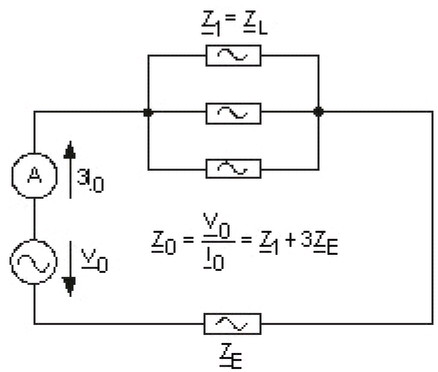
Temperature Correction:	
Material	Al
Measurement Temperature	23°C
Reference Temperature	25°C
Temperature Correction Factor	1.008

Measurements:	R [Ω]	X [Ω]	Z [Ω]	Phi (°)
L1-L2: $Z_{L1} + Z_{L2}$	0.173	1.935	1.943	84.90°
L2-L3: $Z_{L2} + Z_{L3}$	0.168	1.905	1.912	84.96°
L3-L1: $Z_{L3} + Z_{L1}$	0.172	2.105	2.112	85.32°
L1-E: $Z_{L1} + Z_E$	0.509	1.858	1.927	74.68°
L2-E: $Z_{L2} + Z_E$	0.488	1.849	1.913	75.22°
L3-E: $Z_{L3} + Z_E$	0.483	1.860	1.921	75.45°
L1L2L3-E: $Z_{L1}//Z_{L2}//Z_{L3} + Z_E$	0.437	1.194	1.272	69.90°
Intermediate Results				
Z_{L1}	0.088	1.067	1.071	85.26°
Z_{L2}	0.084	0.868	0.872	84.46°
Z_{L3}	0.084	1.037	1.041	85.38°
Z_E from Measurement L1-E	0.421	0.791	0.896	61.99°
Z_E from Measurement L2-E	0.404	0.982	1.062	67.64°
Z_E from Measurement L3-E	0.399	0.823	0.914	64.12°
Z_0 from Measurement L1-E	1.350	3.440	3.696	68.57°
Z_0 from Measurement L2-E	1.296	3.813	4.027	71.23°
Z_0 from Measurement L3-E	1.281	3.505	3.732	69.93°
Line impedance Z_L	0.085	0.991	0.994	85.07°
Ground impedance Z_E	0.409	0.864	0.956	64.69°
Impedance results:	**R [Ω]**	**X [Ω]**	**Z [Ω]**	**Phi (°)**
Positive sequence impedance Z_1	0.085	0.991	0.994	85.07°
Zero sequence impedance Z_0	1.311	3.582	3.815	69.90°

$$\frac{R_E}{R_L}, \frac{X_E}{X_L}$$

$$k_L = \frac{\underline{Z}_E}{\underline{Z}_L} = \frac{1}{3}\left[\frac{\underline{Z}_0}{\underline{Z}_1} - 1\right]$$

$$\frac{\underline{Z}_0}{\underline{Z}_1}$$



Case Study # 2 – U.G. Line

$k_L = Z_E / Z_L$

			k_L [1]	Phi (°)
Residual Compensation Factor			0.961	-20.38°

Calculated Values:

	R [Ω]	X [Ω]	Z [Ω]	Phi (°)
Positive sequence impedance Z_1	0.082	0.991	0.994	85.27°
Error	-4.06%	0.02%	-0.01%	0.20°
Zero sequence impedance Z_0	0.753	2.654	2.759	74.16°
Error	-42.57%	-25.92%	-27.68%	4.26°
Residual Compensation Factor			0.601	-17.24°
Error			-37.44%	3.14°

kL > -37.4% Error

$k_0 = Z_0 / Z_1$

			k_0 [1]	Phi (°)
Residual Compensation Factor			3.836	-15.17°

Calculated Values:

	R [Ω]	X [Ω]	Z [Ω]	Phi (°)
Positive sequence impedance Z_1	0.0820	0.9910	0.994	85.27°
Error	-4.06%	0.02%	-0.01%	0.20°
Zero sequence impedance Z_0	0.7530	2.6540	2.759	74.16°
Error	-42.57%	-25.92%	-27.68%	4.26°
Residual Compensation Factor			2.774	-11.11°
Error			-27.68%	4.06°

k0 > -27.7% Error

Conclusions

- The source of line parameter data in our network models is well understood but is subject to error
- Once accurate model data can change rapidly due to growth and infrastructure expansion
- Understanding the potential sources of data error is critical to evaluating the PAC system performance
- Obtaining accurate and correct line parameters is easier than ever with modern field testing techniques
- Network models are critical to our modern protection systems being applied correctly and securely, but require accurate and up to date parameters that match reality.