



# How Accurate is the Zero Sequence Impedance on Your Transmission Lines?

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## Abstract

Orlando Utilities Commission (OUC) discovered that even one seemingly small error could produce an 18.5% deviation in calculated zero sequence impedance value. The utility began measuring transmission line impedance to analyze different scenarios including underground cable sections, mutually coupled lines, and neighboring utility distribution lines. By comparing values from the collected field-tested impedance data, OUC and Leidos improved the 18.5% zero sequence impedance error between OUC's CAPE model and actual transmission line field measurements. The error was corrected when the neutral conductor on an offset distribution line near the 230kV transmission line was modeled.

This paper discusses how utilities can identify and measure assets that can impact their zero sequence impedance the most. Accurate data results in more effective relay operation, and overall improved relay settings. A conference attendee will take away a better understanding of the impact different parameters have on calculating zero sequence impedance and how to get an accurate zero sequence impedance in the models. Topics include how engineers can calculate zero sequence line impedance, determine the highest priority parameters, and using transmission modeling software to model a variety of parameters including standard tower designs, conductor types, temperature, and distribution lines. Many times, the distribution system is not accounted for even though it has a significant impact on zero sequence impedance.

## Introduction

OUC has been measuring the transmission line impedance for many years to verify computed impedances. When OUC tasked Leidos with computing the line impedance of a newly rebuilt line, the potential for an experiment was perfect. Leidos used PSSCAPE to enter all the line parameters of the transmission line in order to compute a line impedance for the relay settings team. These different parameters included any nearby transmission in the Right of Way (ROW), phase and shield wire characteristics, wire temperatures and tower geometries. The relay settings are calculated based on the computed line impedance results, but OUC measures the line impedance at least 3 days before the line goes back in service. If the calculated vs. the measured is off by more than 5%, the relay settings are adjusted. The first transmission line that Leidos computed was nearly identical to the tested results. However, the next few transmission line impedances computed presented new challenges such as underground portions, distribution underbuild and congested ROWs. The largest deviation between calculated and measured over 3 years was a transmission line with distribution underbuild and that is the case that will be highlighted most in this paper.

## Section 1: System Study

### 1.1 Necessary Parameters to Model a Traditional Transmission Line Accurately

PSSCAPE and other modeling software's like it are extremely helpful in calculating transmission line impedance. There are typically two styles of modeling, Grouped and Tower by Tower. Grouped modeling lumps similar tower designs together to reduce effort but still provide accurate impedance. Tower-by-Tower requires more effort but allows for an individual to create a unique record for each span and results in even higher computed impedance accuracy. But which factors are superfluous and which are crucial to getting an accurate impedance?

#### Initial Assumptions and Data Requirements

Initial assumptions and data requirements necessary prior to modeling transmission lines and perform line constant calculations.

- › **Soil Resistivity** – Due to the variability in soil resistivity based on temperature and weather conditions [1] it can be hard to determine the best practice in assigning a value for this variable. A typical 100  $\Omega$ -m value is used [3], but if models are being created in an area with year-round wet conditions 10  $\Omega$ -m would be used or if the area is dry and rocky or desert like 1000 to 10,000  $\Omega$ -m would be used. Soil resistivity typically has minimal impact to the overall line impedance so assumptions and rules of thumb are acceptable.

- › **Phase Conductors & Shield Conductors** – This data should never be assumed and the data should be verified through either drawings or field verification.
- › **Conductor Spacing** – The conductor spacing or geometry is another piece of data that needs to be entered as close to field conditions as possible. There is some estimations and assumptions that can be made in terms of generalizing multiple spans, but the data should be verified by drawings or in the field.
- › **Tower Height** – Tower height is a piece of data that can vary considerable. Since entering tower heights can be a monotonous and time consuming process and due to the minimal impact the height has on the calculated impedance, a standardized height can be applied for different voltage levels.
- › **Tower Spans** – Depending on the calculation method (Grouped vs Tower-by-Tower) some assumptions may need to be made in terms of the spans. For Grouped modeling, the total length of the section needs to be accounted for and verified through GIS or drawings, but an average spacing is typically applied for the spans. For Tower-by-Tower design, due to the method in which the system is modeled, no assumptions are made and data verification is required through either plan and profile drawings or GIS data.
- › **Line Sag** – As with soil resistivity, line sag is also impacted by temperature and weather conditions but has minimal impact on the calculated line impedance. Due to this minimal impact, line sag data is not typically entered when calculating line impedance.

If an individual has this data and their assumptions in order, modeling lines and calculating line impedance values should be a streamlined and straight forward process.

## 1.2 Newfound Considerations for Transmission Line Modeling

There are a few other non-traditional issues that can affect transmission line impedance modeling such as distribution underbuild, congested ROWs, and underground cable sections. Many utilities neglect distribution underbuild when modeling transmission lines, but the evidence below suggests this may not be the best practice.

- › **Distribution Underbuild** – In the past, most utilities ignored or discounted the importance of modeling distribution underbuild on their transmission lines. After working with OUC to measure the actual line impedance in the field, it was quickly discovered that even a short section of distribution underbuild can have a large effect on the zero sequence impedance. While this is not the only contributing factor to

inaccurate zero sequence impedance, it was the largest factor for this example. Other factors contributing to inaccurate zero sequence line impedance can be difference in soil resistivity, other parallel buried conductors such as pipes and other grounded elements. Inaccurate zero-sequence impedance strongly affects zone reaches and accuracy of impedance-based fault location of distance protection relays in the event of a single line to ground fault [2].

- › **Congested ROWs** – Congested right of ways tend to occur coming out of a generation station or a densely populated area. Below is an example of a congested right of way. In this example, there are 11 transmission lines that share a 700 foot wide ROW for nearly 1 Mile coming out of a generation plant. These congested right of ways produces lots of mutual coupling for the transmission lines in question and have a large affect on zero sequence impedance. This is accounted for in PSSCAPE. Figure 1 below shows an example from CAPE of a congested ROW.

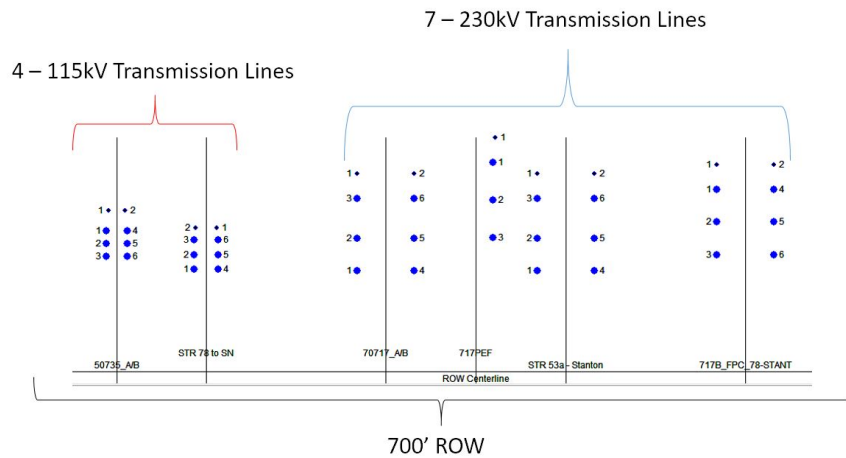


Figure 1

- › **Underground Cable Sections** – These are added to the modeled as a manual entry using the manufacture data. Knowing that the transmission line was going to be tested, the team was excited to see how the modeling program performed with the underground cable section. The team was pleased to report the measurement was spot on with the expected value. With different environmental factors that are impossible to account for in a modeling program, it can be difficult if you don't know the area. A large gas pipe running along underground transmission lines could affect the zero sequence considerably.

## Section 2 System Study

### 2.1 Example System Study Parameters

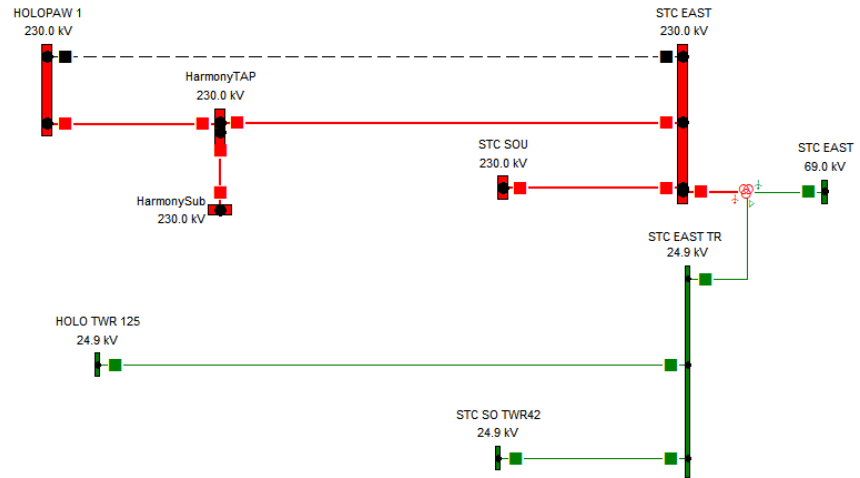


Figure 2

Figure 2 above shows the example in question's layout. There is an 8.2 mile transmission line from STC East to Holopaw. There is also (2) 25kV distribution lines underbuilt, with 1 circuit in the ROW for the majority of the line. It is a double circuit 230kV transmission line for the first 2.2 miles then continues on as a single circuit for the remaining 6 miles. The 25kV distribution underbuild follows the exact same configuration, with one circuit peeling off after 2.2 miles and the other continuing towards Holopaw.

The transmission line characteristics, such as conductor type, vary for each transmission line used in the analysis. Only sections of circuits that are parallel to the 7-29PEC-HOL transmission line were modeled and therefore the conductor information below does not necessarily represent the conductors for the entire line. The following characteristics highlight the differences in conductors between the circuits.

The St. Cloud East to Holopaw transmission line was analyzed with the following conductors:

- › 7-29PEC-HOL (St. Cloud East to Holopaw)
  - 1222 kcmil ACCC "Cardinal"
  - Alcoa Fujikura 55/443 48 count OPGW
  - "DNO-9324", 0.507 inch AFL Telecommunications 72 fiber count OPGW

The existing transmission line conductor characteristics located in the same corridor as the St. Cloud East to Holopaw transmission lines are as follows:

- › 7-2733
  - ACSR/AW Cardinal 954 kcmil 54/7 type overhead conductor
    - Parallels 7-29PEC-HOL line for the first 2.32 miles on double circuit tower

The rebuilt St. Cloud East to Holopaw circuit will also have (2) 25kV distribution underbuild lines. It was assumed that the distribution circuit will be in-service at the time the St. Cloud East to Holopaw 230kV transmission line goes into service and therefore the circuit was included in the model to study the effects of the mutual coupling. The conductor information is as follows:

- › 25kV distribution underbuild #1 (First 2.32 Miles out of STC East on the 7-29PEC-HOL)
  - 477 AAC “Cosmos” type overhead conductor
  - AAC “Oxlip” 4/0 7 type overhead neutral conductor
- › 25kV distribution underbuild #2 (Used on 7.59 miles of the 8.13 miles on 7-29PEC-HOL)
  - 477 AAC “Cosmos” type overhead conductor
  - AAC “Oxlip” 4/0 7 type overhead neutral conductor

## Section 3 Study Results

### 3.1 Results of System Study

Once the field test results were compared to the calculated values, it was obvious something was off. The zero sequence impedance difference was almost 20%. Leidos had to find out why there was such a discrepancy. Was there a large gas pipeline running along the transmission line? Was the soil resistivity that far off from assumed? Was there another neighboring utility’s distribution line not on the drawings? These were all real possibilities, but finding out exactly which one was a process. Looking back through the drawings, everything was modeled properly, so Leidos went to the field to verify the drawings were correct. Upon further inspection of the line, it was determined that the neutral conductor for the last few miles of distribution line had not been modeled properly. It was a neighboring utility’s distribution line, so the prints provided didn’t have all the accurate information. Once the proper neutral conductor was added into the model, it corrected the zero sequence impedance so that the error was within 1.5% as shown below in table 3.

### Impedance Results from Field Test

Table 1

Result	R [ $\Omega$ ]	X [ $\Omega$ ]	Z [ $\Omega$ ]	Phi ( $^\circ$ )
Positive sequence impedance Z1	0.773	5.769	5.821	82.37 $^\circ$
Zero sequence impedance Z0	4.052	13.267	13.872	73.02 $^\circ$

### Calculated Values

Table 2

Result	R [ $\Omega$ ]	X [ $\Omega$ ]	Z [ $\Omega$ ]	Phi ( $^\circ$ )
Positive sequence impedance Z1	0.772	5.946	5.996	82.60 $^\circ$
Error	-0.08%	3.06%	3.01%	0.23 $^\circ$
Zero sequence impedance Z0	3.973	15.627	16.124	75.74 $^\circ$
Error	-1.96%	17.78%	16.23%	2.72 $^\circ$

### Calculated Values (Corrected for Neutral Wire)

Table 3

Result	R [ $\Omega$ ]	X [ $\Omega$ ]	Z [ $\Omega$ ]	Phi ( $^\circ$ )
Positive sequence impedance Z1	0.762	5.777	5.827	82.49 $^\circ$
Error	-0.08%	3.06%	0.10%	0.15%
Zero sequence impedance Z0	3.678	13.171	13.675	74.40 $^\circ$
Error	-1.96%	17.78%	-1.42%	1.89%

## Section 4: Conclusion

### 4.1 Key Takeaways

While the error was discovered and corrected, it highlights that a model is only as good as the information provided to it. Out of all the utilities Leidos has had the pleasure of supporting, OUC is the only one that measures their line impedance. IEEE Standard 1870-2019 Guide for the Parameter Measurement of AC Transmission Lines points out that in the study of 40 transmission lines, the values for the calculated zero sequence impedance had values ranging from -20% to +35% of the measured values. This means that for ground faults, instead of protecting 90% of the transmission line, the relay was actually protecting as high as 129% of its zone, which obviously is over-reaching and will cause the relay to have a misoperation. Similarly, for a fault placed at 4.375 miles of the line, the fault location for a C-G fault shows it at 3.05 miles. These are just 2 examples of how measuring your transmission line can improve proper relay operations and give better locations for faults [2].

## References

[1] IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System," in IEEE Std 81-2012 (Revision of IEEE Std 81-1983) , vol., no., pp.1-86, 28 Dec. 2012, doi: 10.1109/IEEESTD.2012.6392181.

[2] "IEEE Guide for the Parameter Measurement of AC Transmission Lines," in IEEE Std 1870-2019 , vol., no., pp.1-99, 8 July 2019, doi: 10.1109/IEEESTD.2019.8755346. (IEEE 1870 Standard)

[3] W. H. Kersting and R. K. Green, "The application of Carson's equation to the steady-state analysis of distribution feeders," 2011 IEEE/PES Power Systems Conference and Exposition, Phoenix, AZ, 2011, pp. 1-6, doi: 10.1109/PSCE.2011.5772579.

## Appendix A: CAPE Line Constant Raw Data

### Line Constant Module Calculations

```
*****
Report Date       : Fri Mar 20 10:47:27 2020
Included Categories: Include category checking is not active
Excluded Categories: Exclude category checking is not active
Study Date        : 3/1/2020
Selected Line Name : St. Cloud East - Holopaw; From: 7431 STC EAST      To:
5798 HarmonyTAP   Ckt:2
*****
```

As an aid in setting distance relays, the worst case positive sequence line impedance, assuming untransposed phases, is:  
 0.6870 +j 4.5284 Ohms, or 4.5803 Ohms @ 81.37 degrees.  
 A zone 1 reach set to this value will not overreach the line.

Line kV: 230.00  
 Length: 6.81 miles  
 Surge impedance: 343.28 ohms    Loading: 154.101 MW

Two Port Data (shunt values are for entire line)

	-----Ohms-----		-----MicroMhos-----	
	Series R	Series X	Shunt G	Shunt B
Positive Seq New	0.63730	4.83268	0.00009	41.36506
Positive Seq Old	0.63678	4.83071	0.00009	41.36601
Negative Seq New	0.63730	4.83268	0.00009	41.36506
Negative Seq Old	0.63678	4.83071	0.00009	41.36601
Zero Seq New	3.05178	11.02649	0.00013	23.51027
Zero Seq Old	2.80036	10.91573	0.00012	23.51869

### Line Section Results

```
Section Number: 1    ID: Section 1
Right of Way: St. Cloud East - Holopaw
Length: 2.32 miles    Impedance Source: Line Constants
Tower String ID: Section 1
Tower ID: 230DSBP-1 OUC
Tower Design Title:
Tower Design Voltage: 230 kV
Neutral Conductor type: OPT-GW
                        code: DNO-9324
                        size: 0.507
                        segmented: No
Neutral Conductor type: OPT-GW
                        code: Alcoa Fujikura
                        size: 55/443
                        segmented: No
Neutral Conductor type: AAC
                        code: Oxlip
```

size: 4/0  
 segmented: No  
 Neutral Conductor type: AAC  
 code: Oxlip  
 size: 4/0  
 segmented: No  
 Phase Conductor type: AAAC  
 code: ACCC Cardinal  
 size: 1222 kcmil  
 number per bundle: 1

	-----Ohms-----		-----MicroMhos-----	
	Series R	Series X	Shunt G	Shunt B
Positive Seq New	0.21559	1.62235	0.00000	14.32421
Positive Seq Old	0.21559	1.62235	0.00000	14.32421
Zero Seq New	0.93161	3.66247	0.00000	8.63420
Zero Seq Old	0.93161	3.66247	0.00000	8.63420

Section Number: 2 ID: Section 2  
 Right of Way: St. Cloud East - Holopaw  
 Length: 1.26 miles Impedance Source: Line Constants  
 Tower String ID: Section 2  
 Tower ID: 230kV Single ckt w/ Underbuild OUC  
 Tower Design Title:  
 Tower Design Voltage: 230 kV  
 Neutral Conductor type: OPT-GW  
 code: DNO-9324  
 size: 0.507  
 segmented: No  
 Neutral Conductor type: AAC  
 code: Poppy  
 size: 1/0  
 segmented: No  
 Phase Conductor type: AAAC  
 code: ACCC Cardinal  
 size: 1222 kcmil  
 number per bundle: 1

	-----Ohms-----		-----MicroMhos-----	
	Series R	Series X	Shunt G	Shunt B
Positive Seq New	0.11782	0.90147	0.00000	7.59324
Positive Seq Old	0.11776	0.90108	0.00000	7.59326
Zero Seq New	0.62313	2.20724	0.00000	4.05378
Zero Seq Old	0.57107	2.18177	0.00000	4.05411

Section Number: 3 ID: Section 3  
 Right of Way: St. Cloud East - Holopaw  
 Length: 634 feet Impedance Source: Line Constants  
 Tower String ID: Section 3  
 Tower ID: 230kV Single ckt  
 Tower Design Title:

Tower Design Voltage: 230 kV  
 Neutral Conductor type: OPT-GW  
     code: DNO-9324  
     size: 0.507  
     segmented: No  
 Phase Conductor type: AAAC  
     code: ACCC Cardinal  
     size: 1222 kcmil  
 number per bundle: 1

	-----Ohms-----		-----MicroMhos-----	
	Series R	Series X	Shunt G	Shunt B
Positive Seq New	0.01105	0.08604	0.00000	0.72044
Positive Seq Old	0.01105	0.08604	0.00000	0.72044
Zero Seq New	0.06028	0.23888	0.00000	0.36506
Zero Seq Old	0.06028	0.23888	0.00000	0.36506

Section Number: 4 ID: Section 4  
 Right of Way: St. Cloud East - Holopaw  
 Length: 3.11 miles Impedance Source: Line Constants  
 Tower String ID: Section 4  
 Tower ID: 230kV Single ckt w/ adjacent distrib  
 Tower Design Title: Adjacenet distribution  
 Tower Design Voltage: 230 kV  
 Neutral Conductor type: OPT-GW  
     code: DNO-9324  
     size: 0.507  
     segmented: No  
 Neutral Conductor type: AAC  
     code: Poppy  
     size: 1/0  
     segmented: No  
 Phase Conductor type: AAAC  
     code: ACCC Cardinal  
     size: 1222 kcmil  
 number per bundle: 1

	-----Ohms-----		-----MicroMhos-----	
	Series R	Series X	Shunt G	Shunt B
Positive Seq New	0.29287	2.22296	0.00001	18.72659
Positive Seq Old	0.29241	2.22137	0.00001	18.72751
Zero Seq New	1.43698	4.91827	0.00001	10.45679
Zero Seq Old	1.23759	4.83298	0.00001	10.46489

Mutuals for Primary Line; 230.00 kV  
 and line: Distribution underbuild #1; From: 7447 STC EAST TR To: 5796  
 Bus\_5796 Ckt:1; 24.90 kV  
 Source of old mutual impedance: Calculated by LC

		-----Ohms-----		MicroMhos		
B3	B4	Series R	Series X	Shunt B	B1	B2

```

-----
Zero Seq New      2.18705    3.49665   -3.18858    0.00000    1.00000
0.00000    0.87793
Zero Seq Old      1.85835    3.30680                0.00000    1.00000
0.00000    0.87793
  
```

```

+++++++
Warning: the components for the above mutual coupling are disjoint.
The B factors represent the extent of the coupling, but the coupling
is not uniform in this region. Sliding faults along this line may
not be correct.
  
```

```

+++++++
Warning: the impedance per unit length of the individual components
for the above mutual coupling is not consistent. Sliding faults
along this line may not be correct.
  
```

Sorted B factor components for the primary line

B1	B2	Rm	Xm	Section	% Len	Len Ft	Xm/Mi
0.0000	0.3407	0.5594	1.0186	1	34.07	12249	0.4391
0.3407	0.5257	0.4990	0.8440	2	18.50	6652	0.6699
<=== 633 foot discontinuity							
0.5433	1.0000	1.1287	1.6341	4	45.67	16420	0.5255

Sorted B factor components for the coupled line

B3	B4	Rm	Xm	Section	% Len	Len Ft	Xm/Mi
0.0000	0.3045	0.5594	1.0186	1	30.45	10947	0.4913
0.3045	0.4698	0.4990	0.8440	2	16.54	5945	0.7496
0.4698	0.8779	1.1287	1.6341	3	40.81	14674	0.5880

and line: Distribution underbuild #2; From: 7447 STC EAST TR To: 5797 Bus\_5797 Ckt:2; 24.90 kV

Source of old mutual impedance: Calculated by LC

		-----Ohms-----			MicroMhos	
B3	B4	Series R	Series X	Shunt B	B1	B2
Zero Seq New		0.55921	0.99112	-0.52637	0.00000	0.34068
0.00000	1.00000					
Zero Seq Old		0.55921	0.99112		0.00000	0.34068
0.00000	1.00000					

and line: 7-2733; From: 7431 STC EAST To: 7432 STC SOU Ckt:1; 230.00 kV

Source of old mutual impedance: Calculated by LC

		-----Ohms-----			MicroMhos	
B3	B4	Series R	Series X	Shunt B	B1	B2
Zero Seq New		0.72149	1.70412	-2.90894	0.00000	0.34068
0.00000	1.00000					

Zero Seq Old            0.72149      1.70412                    0.00000      0.34068  
 0.00000    1.00000

\*\*\*\*\*  
 Report Date            : Tue Mar 24 10:52:29 2020  
 Included Categories: Include category checking is not active  
 Excluded Categories: Exclude category checking is not active  
 Study Date            : 3/1/2020  
 Selected Line Name : St. Cloud East - Holopaw; From: 5798 HarmonyTAP    To:  
 2882 HOLOPAW 1      Ckt:2  
 \*\*\*\*\*

As an aid in setting distance relays, the worst case positive sequence line impedance, assuming untransposed phases, is:  
 0.1304 +j 0.8896 Ohms, or 0.8991 Ohms @ 81.66 degrees.  
 A zone 1 reach set to this value will not overreach the line.

Line kV: 230.00  
 Length: 1.32 miles  
 Surge impedance: 346.10 ohms    Loading: 152.846 MW

Two Port Data (shunt values are for entire line)

	-----Ohms-----		-----MicroMhos-----	
	Series R	Series X	Shunt G	Shunt B
Positive Seq New	0.12420	0.94387	0.00000	7.94760
Positive Seq Old	0.12420	0.94387	0.00000	7.94760
Negative Seq New	0.12420	0.94387	0.00000	7.94760
Negative Seq Old	0.12420	0.94387	0.00000	7.94760
Zero Seq New	0.62624	2.14463	0.00000	4.37298
Zero Seq Old	0.62624	2.14463	0.00000	4.37298

Line Section Results

Section Number: 1    ID: Section 5  
 Right of Way: St. Cloud East - Holopaw  
 Length: 1.32 miles    Impedance Source: Line Constants  
 Tower String ID: Section 5  
 Tower ID: 230kV Single ckt w/ adjacent distrib  
 Tower Design Title: Adjacenet distribution  
 Tower Design Voltage: 230 kV  
 Neutral Conductor type: OPT-GW  
                                  code: DNO-9324  
                                  size: 0.507  
                          segmented: No  
 Neutral Conductor type: AAC  
                                  code: Poppy  
                                  size: 1/0  
                          segmented: No  
 Phase Conductor type: AAAC  
                                  code: ACCC Cardinal  
                                  size: 1222 kcmil  
                          number per bundle: 1

How Accurate is the Zero Sequence Impedance on Your Transmission Lines?

	-----Ohms-----		-----MicroMhos-----	
	Series R	Series X	Shunt G	Shunt B
Positive Seq New	0.12420	0.94387	0.00000	7.94760
Positive Seq Old	0.12420	0.94387	0.00000	7.94760
Zero Seq New	0.62624	2.14463	0.00000	4.37298
Zero Seq Old	0.62624	2.14463	0.00000	4.37298

Mutuals for Primary Line; 230.00 kV  
 and line: Distribution underbuild #1; From: 7447 STC EAST TR To: 5796  
 Bus\_5796 Ckt:1; 24.90 kV  
 Source of old mutual impedance: Calculated by LC

B3	B4	-----Ohms-----		MicroMhos		
		Series R	Series X	Shunt B	B1	B2
Zero Seq New		0.32670	0.47299	-0.51588	0.00000	0.68186
0.88140	1.00000					
Zero Seq Old		0.32670	0.47299		0.00000	0.68186
0.88140	1.00000					