69th Annual Conference for Protective Relay Engineers

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

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Abstract - The paper identifies real world issues where the engineering calculations used to compute the variables that go into a power system network model can fall short of reality. This not only impacts the viability of the simulation tool used, but worse the accuracy of the data it provides to configure and set today's modern IED protection relays. The faulty result is often hidden until a fault of circumstance occurs to reveal the issue. But what data of the model needs correction?

The core issue is that modern power systems evolve over time, as does the world around it. Infrastructure expansion of all industries affect the power system's physical properties (ground impedance, mutual coupling, switched configurations, CT/VT performance, etc…) and this in turn directly impacts the variables and parameters we use to model it. This has become critical today where correct modeling data plays a key role in the IED settings, the way we test and commission them, and especially their operational performance and security.

The paper uses several real world test cases to illustrate where engineering data becomes faulty at inception or over time and that actual measurements of systems parameters are required to correct that data. Proving the new data as accurate requires a fast and flexible power system simulator where before and after performance of the IED setting changes can be proven to show correct secure protection actions. The paper explains the techniques, tools, and process used to correct the modeling data and ensure modeling accuracy.

Index Terms— Protection, distance, modeling, testing, relay, simulation, performance

1 Introduction

Between 80-90% of all power system faults involve ground, mainly due to lighting. Many protective relaying schemes depend on ground distance protection to accurately sense and locate ground faults on multi-terminal MV 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 and other undesired consequences, such as under tripping or unintended reclosing operations.

When these problems are exposed, it can result in major power system disturbances, such as the US/Canada Northeast blackout of 2003. Correct application and settings of protective devices, particularly distance relays, became the subject of heavy scrutiny. All procedures dealing with accurate distance relay settings was a major topic of discussion by NERC/FERC, electric power utilities, and the IEEE Power Systems Relay Committee. It becomes apparent very quickly that the accuracy of line parameter values and the modeling data were a topic too.

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)

Relay manufacturers have different methods of calculating zero-sequence compensation, also known as the "k factor", but generally it is defined as the ratio between the zero-sequence impedance Z0 and the positive-sequence impedance Z1 of a given transmission line. The k factor is used to "correct" the ground impedance calculation so that the total fault loop calculation is accurate. *Therefore, if the k factor is not accurate, the calculated fault reach/distance will be incorrect.*

2 Determining Line Constants

Transmission line impedances (including k factor) are typically calculated by line constants programs. Due to the large number of variables required, line parameter calculations are subject to some error, but particularly in the zero-sequence impedance value of the line. For example a key parameter is soil resistivity, utilities often assume fixed soil resistivity values (10Ωm, 100Ωm, etc.) applied across their system models. Even though they know the transmission line spans many different geological areas. Due to the uncertainties related to soil resistivity and actual transmission tower grounding effectiveness, the calculation of Z0 of a given line is just more susceptible to error than is Z1. This is because the calculation of Z1 is independent of the ground path impedance. For parallel transmission lines, the accurate calculation of zero-sequence mutual impedance Z0M is also prone to the errors described above.

Such errors in the estimation and calculation of line parameters will affect accuracy of settings used in transmission line protective devices, particularly in ground distance and ground overcurrent relays, causing them to either under or overreach, resulting in a potential misoperation. In order words, relay sensitivity to detect ground faults will be affected.

Additionally, Z0 and Z1 are used as inputs by many digital relays to calculate the location from the line terminal to the fault. Accurate fault location data is needed by utility crews to promptly locate the cause and repair damaged lines as quickly as possible. Moreover, short circuit and coordination studies also depend on accurate modeling data to enable the protection engineer to generally set relays correctly.

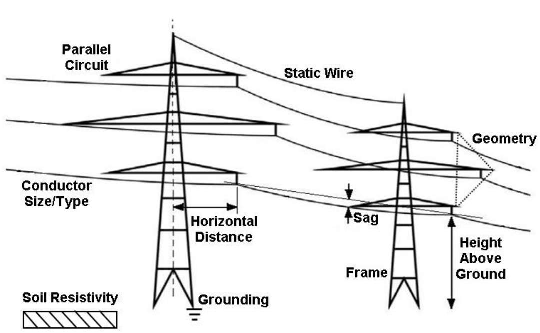
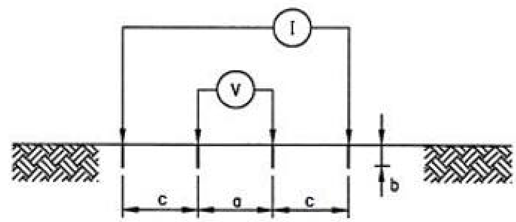


Fig. 1: Typical Line Constants data sources

3 Soil Resistivity Issues

There are two methods used for soil resistivity measurement: 1) the Wenner method and 2) the Schlumberger method. Both use a variation of four point injection/measurement illustrated in Fig 2. The Werner method is stricter requiring uniform electrode spacing and depth, whereas the Schlumberger method is more simplified requiring only the spacing between the current and voltage electrodes to be the same with uniform depth.



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

Fig. 2: Schlumberger resistivity method

Both give suitable results with resistivity ρE expressed as V/I. Soil resistivity is influenced by moisture, temperature, and chemical content. But most important for our application is the influence of electrode depth and other conductive objects.

A general warning known when performing these measurements is that they are affected by existing grounded electrodes and buried conductive objects that affect the test current flow pattern. This is particularly true for large and long parallel objects. So any objects in or crossing the right of way (ROW) of a transmission line (e.g. pipeline, etc..) will affect the results.

And both IEEE and IEC standards recommend using seasonal variations for resistivity in transmission designs due to the influence of moisture/temperature. (A winter scaling of 5-6 times that of summer is cited!) So what happens in winter for a relay where the k-factor is off by 20% in summer?

In the past utilities would make soil resistivity checks when a ROW was surveyed. Results were recorded on the platen for that ROW and the values later averaged, then converted to an Ohm/mile value for the line constants program. But this required time and manpower and the practice was eventually eliminated in favor of using more cost effective sources like USGS, the FCC, and even USDA.

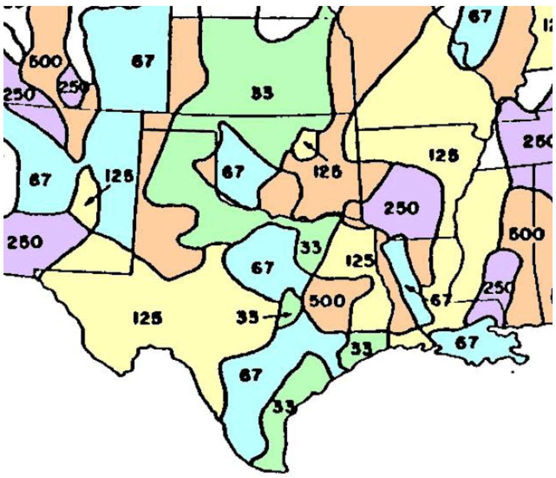


Fig. 3: USDA Earth Resistivity by area (Ω /m)

However these sources provided different values for the same geographical area. Using the USGS data one could argue that an average of 50 Ohm/m was good enough even though depending on electrode depth >15m this value could climb to 600 Ohm/m. The same area according to the USDA map (Fig 3) might yield 33 Ohm/m to 500 Ohm/m.

Still, buried infrastructure drastically affects this local resistivity value and most every urban area of the USA has experienced growth. Fig 4a & 4b shows a comparison of the Houston South Loop area from 1960 to 2015. Notice the difference? Yep, it went from cow pasture to a 10 lane expressway called 610 Loop with a mega sports complex and residential/commercial expansion to the north and major industrial expansion to the south. But it's not finished yet, these areas are constantly evolving and growing.

Along with roads, there are pipelines, rail, water, sewer, wells, major buildings and even new transmission ROW to serve the growth. Each addition alters the ground resistance between any two points in the electric grid affecting the protection settings and influencing performance.

Fig. 4a: Houston South Loop area 1960 (Google earth)

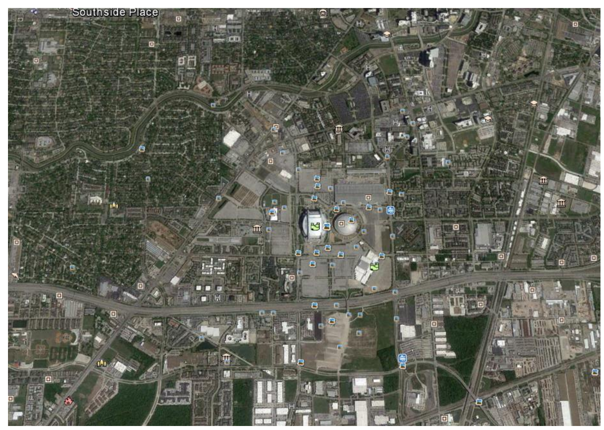


Fig. 4b: Houston South Loop area 2015 (Google earth)

4 Alternative to Estimating Resistivity

The alternative to estimating the resistivity for the line parameter calculation is by taking actual measurements on the suspect transmission line to accurately determine its impedances and k factor. Measuring the line impedance using the proper techniques, equipment, and safety precautions provides the opportunity to eliminate the uncertainties previously described. In the recent past, line parameter measurement was considered prohibitive and costly, since it required large high-powered equipment to overcome the nominal frequency interferences of the grid. (50 or 60 Hz) But with modern digital technology off-nominal frequency injection is not only possible but also cost effective to overcome these challenges with proper primary injection equipment and safety devices. (Fig 5)

Overall, seven measurements per line are made, three for each Ph-Ph and Ph-N loop and one for the 3Ph-N loop. Current injection varies between 10-100A depending on line length and charging voltage. Off frequency injections allow for smaller currents without interference from system frequency while selective digital filter measuring ensures high accuracy of the measured voltage and current.

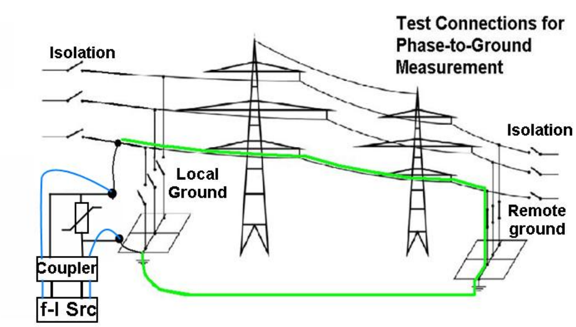


Fig. 5: Line Measurement Method Ph-Gnd

Redundancy in measurements allow reliability crosschecks and calculation of individual k-factors for each phase. Results are post-processed in a spreadsheet for quick calculations and flexible reporting. But the proof is in doing it and comparing the results, so a few test cases are in order.

5 Utility Test Case #1 - 69kV System

An eastern utility's 69kV sub-transmission system had experienced nusiance trips and the distance relay settings were suspected. After much trial and error in adapting settings they opted to make actual measurements of the line parameters.

Out of 16 lines measured, 15 had higher zero sequence magnitudes than previously estimated. The average difference was 51% between calculated vs. measured, with the error ranging from 10% to 107%. However, the positive sequence values were all within a modest 3.5% error.

Based on these measured values the K-Factor error range was -15% to +147%! (Fig 5) When these new measured values were used in back testing some of the previous line misoperations, the results matched the historical fault records. With this, a program was put in place to measure the remaining 69kV system and adapt settings as required.

Line	Measured		Calculated		Error	
	k0	k0ang	k0	k0ang	k0%	k0ang
B-262	0.67	-5.07	1.20	6.13	79.90	11.20
G-163	0.58	5.89	1.20	3.96	108.25	-1.93
U-151	0.70	0.69	1.12	9.46	61.25	8.76
O-67	1.02	-32.63	1.75	-27.50	71.40	5.14
Z-26	0.84	-17.62	2.07	-11.95	147.40	5.67
A-27	1.10	-16.96	2.06	-10.91	88.16	6.05
Q-225	1.40	-5.40	1.18	2.18	-15.68	7.58
O-93	1.27	-28.02	1.73	-28.25	36.16	-0.22
Z-182	1.15	-11.33	2.12	-12.26	84.17	-0.93
U-411	0.98	-15.36	2.00	-15.14	103.58	0.21
I-269	1.38	-14.01	1.26	-2.40	-8.54	11.61
D-212	1.29	0.62	1.11	9.11	-14.36	8.49
V-568	0.73	-5.05	1.35	5.86	84.81	10.91
A-573	1.41	2.61	1.31	-7.02	-6.73	-9.63
O-301	0.82	-0.37	1.08	10.61	32.70	10.98
L-272	0.90	-10.07	1.79	-8.90	97.56	1.17

Fig. 5: Results of 16 Measured 69kV Lines

The utility attributed these variances to the infrastructure build out around and in the 69kV grid over a 40 year span and the assumed 100 ohm/m resistivity standard they had been using.

6 Utility Test Case #2 - 230kV OHL

This western US utility had experienced some single-phase to ground nuisance trips after upgrading some segments of a 230kV overhead line which now used portions of mixed use ROW's that paralleled a major highway and railway. They suspected incorrect ground settings.

The suspect line segment became available due to a short construction window requiring its outage, giving the opportunity to make the line impedance measurements. They were conducted in early spring 2014 and the process was completed within a 3 hour window. The line was to be put in service a few days later and the utility wanted to update and retest the protection settings if needed.

The results (Fig 6) showed that the calculated residual compensation factor K_L was 66% larger than measured. The utility quickly adjusted the settings for both ends of the line and recommissioned the protection relays. The line was placed back in service on schedule.

Measurement Results - Overall

$k_L = Z_E / Z_L$				
			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	15.62%	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°

Fig. 6: Error of 230kV Line Parameters Calculated vs Measured

The utility reviewed the previous modeling data and concluded that the influence of the major highway and parallel railway plus existing lines in the ROW contributed to the reduced zero sequence impedance and corresponding K factor value.

7 Utility Test Case #3 - 230kV UGL

Even cases where the design and data seems extremely well known, the actual results can still surprise you. This utility had a well-designed pair of 230kV stations linked with a 5.8 mile underground line consisting of 2x3500k CMIL copper XLPE cable per phase.

There are 16 splices in that length with single bonded sheath and a 3-phase ground box at each splice point connected to a dual 4/0 ground conductor from end to end. (Fig 7) Their calculations showed an expected Z1 of 1Ohm@85deg and a Z0 of 2.76 Ohm@74deg.

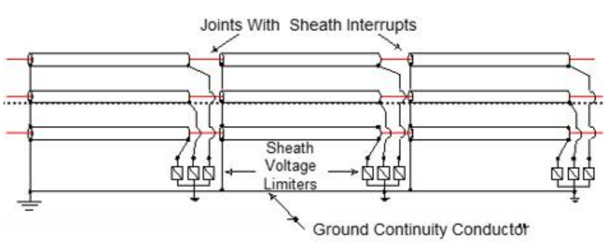


Fig. 7: Detail of Segments, Splices, Gnd Box

Before they put this critical circuit into service they wanted to measure the line impedances to verify the design and calculations since they planned on additional underground lines in the future. Being new construction it was very easy to schedule the measurements once completed.

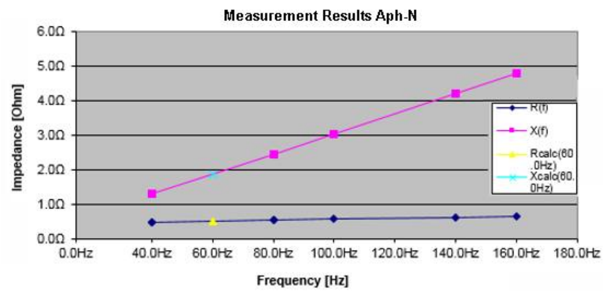


Fig. 8: Loop Measurement @ multiple frequencies

Once completed, the measurements were processed and analyzed, and the results surprised most everyone. The positive sequence impedance had been calculated as 1 Ohm @ 85 degrees and the measured value came in at 0.994 Ohm @ 85.27 degrees. A total error of only -0.01%! This measurement accuracy impressed us all.

But the zero sequence impedance turned out to be a little different. It was highly regarded that the calculated value of 2.76 Ohm @ 74 degrees would be accurate too because of the continuous 4/0 ground cable, sheath bonding of each segment, and the "known" soil resistivity. So when the measured result was 3.815 Ohms @ 69.9 degrees, most could not believe it. This was an error of over 27% and 4 degrees! The resulting K factor calculation error was -37.44% over the measured values. (Fig 9)

$k_L = Z_E / Z_L$	230kV UG Cable			
			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°

Fig. 9: Final results of 230kV UG Line Analysis

The measurements were repeated three more times from Station A and then moved to Station B and repeated there three times. All measured results were repeatable. Since the construction of the UG cable system was explicit, and the positive sequence values so spot on, it meant something along the actual path between the two stations had to be influencing the measurements.

In fact, the UG cable route was not line of sight between the stations, but routed via a ROW that took the long way to get there. Between the UG cable and line of sight of the two stations were multiple railway lines and two pipelines that bisected it. The overall effect was a series – parallel resistance making the overall ground resistance higher. This was good to know because of the additional planned UG circuits for the area.

8 Conclusions

When using line constants programs the known construction variables are easily obtainable and produce very accurate positive sequence impedance calculations. However not having the correct data for the soil resistivity and ground current flow path have proven critical. The zero sequence calculations cannot be relied on unless the correct data is used and this might only be available by direct measurement. Further, these calculations are used in nearly all power system modeling programs including real-time digital simulators are only as good as the data in them.

With new technology comes new possibilities, past issues of confirming this data by looking to fault event values recorded by our protection relays which are filtered to line frequency may improve as more devices move to unfiltered event samples. Regardless of the source, the correct data is a must for correct settings to be applied especially where the K factors are involved.

9 References

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10 Biography

Benton Vandiver III received BSEE from the University of Houston in 1979.

He was with Houston Lighting & Power for 14 years and Multilin Corp. for 4 years before joining OMICRON electronics in 1995 where he is currently Principal Engineer residing in Houston, TX. A registered Professional Engineer in TX, he is also an IEEE / PSRC senior member, USNC member, CIGRE corresponding member. He holds a US Patent for "Communication-based Testing of IED's" and has authored, co-authored, and presented over 90 technical papers and published numerous articles.