Comparison of Methods to Determine Transmission Line Impedance

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Background

In power systems, there are many applications that are dependent on the impedance of every transmission line and transformer in the system. Planning models, SCADA/EMS operating models, fault study models, relay protection settings, and fault analytics are some of these applications. The accuracy of these applications is only as accurate as the calculated or measured impedances of the lines and transformers.

Transformers are relatively simple to determine the impedance of through testing by the manufacturer due to their smaller size, and many manufacturers provide impedance results from IEEE standard transformer tests. Transmission lines are much more complicated to determine the impedance of due to their length, construction build, environment, and other factors. The impedances of transmission lines can therefore be much more inaccurate than transformers. The focus of this paper is on transmission line impedance and their inaccuracies, presented from multiple methods of determining transmission line impedances used on Dominion Virginia Power's transmission network.

Traditional Method

The traditional method of calculating transmission line impedance, still in use everywhere today, is ideal because it significantly reduces the number of calculations required. This was critical when impedance calculations were performed first by hand, then by mainframe computers, and then by the first personal computers. When the calculations were performed with these tools, both time (for humans) and processing power (for computers) were limited, so performing thousands of calculations to determine the impedance of one transmission line was not realistic, and often not possible.

In order to reduce the number of impedance calculations, the traditional method requires the detailed design of a transmission line along its entire path, including tower types, conductor types, static wire types, and the spatial arrangements of the wires. From the design, a transmission line designer or protection engineer will follow the transmission line design and try to find homogeneous line sections where the wire types, tower types, and spatial arrangement of the wires is relatively the same. Other factors that could define a new section include other transmission lines in the right-of-way that enter or leave the section, going from overhead to underground lines, and transposed versus untransposed phase connections.

Consider a 65-mile 500kV line that has untransposed phase conductors. It is known from the design of this line that there are 262 structures in total, and the phase and static conductors are the same throughout all 65 miles. It is also determined that the majority of the towers are H-frame towers with flat phase configurations, but line sections at the beginning and end of the line have H-frame towers with triangle phase configurations. There are no other transmission lines in the right-of-way (ROW) with this 500kV line.

With this design information known, a designer or engineer would define three homogeneous line sections, as shown in Figure 1.

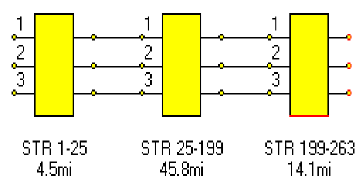

Figure 1 – Three homogeneous line sections for a 65-mile 500kV transmission line [1].

The first homogeneous section is 4.5 miles long from Structure 1 to Structure 25. This is one of the two sections that has the triangle phase configurations. The second section is 45.8 miles long from Structure 25 to Structure 199. This is the majority of the line that has flat phase configuration on H-frame towers. The third and final section is 14.1 miles long from Structure 199 to Structure 263. This section has the same flat phase configuration as the first section.

It is already possible to see how the traditional method reduces the number of calculations to produce a result. This 65-mile 500kV line example has 262 structures. If a number of homogeneous line sections are not defined, the impedance of every span of wire between all 262 structures would have to be calculated. With three homogeneous sections defined, that is requires less than 2% of the calculations required when using all 262 structures. While the number of calculations has been reduced, impedance errors have been introduced because in any homogeneous section, any towers or conductors that vary from the section average are not accounted for in the traditional method.

Figure 2 shows another example of homogeneous line sections for a 34-mile 115kV untransposed transmission line.

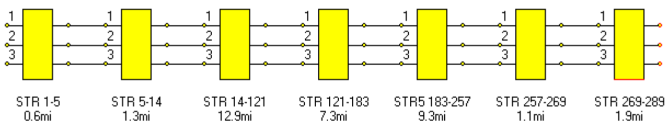

Figure 2 – Seven homogeneous line sections for a 34-mile 115kV transmission line [1].

The next step with the traditional method is to define all the parameters for each homogeneous section. In each homogeneous section, all transmission lines in the right-of-way must have the following parameters defined:

- Phase & Static Conductor spatial arrangement
- Phase & Static Conductor type with electrical parameters
- Static Conductors segmented or not
- Bundled Conductors
- Soil Resistivity
- Conductor Sag
- Voltage level

To simplify or reduce the calculations even further (and therefore introducing more errors), some of these parameters are often averaged or ignored with the traditional method. Conductor sag is often ignored, assuming the line between towers is straight with no sag. Soil Resistivity is often averaged across entire power grids based on the geographic location and the most common types of soil present, similar to the values defined in Table 1.

Soil Type	Soil Resistivity (Ohm-m)
Moist soil	30
Farmland, clay	100
Sandy clay	150
Moist sand	300
Moist gravel	500
Dry sand, dry gravel	1000
Rock	30,000

Table 2 – Common Soil Resistivity values [2].

Figure 3 shows an example of the conductor spatial arrangement in a ROW with three transmission lines. This spatial arrangement information is required for the homogeneous line sections of each of the three lines in the ROW. It is often the case with these conductor arrangements that the distances are calculated using rulers and hand calculations. This is another parameter where errors can be introduced.

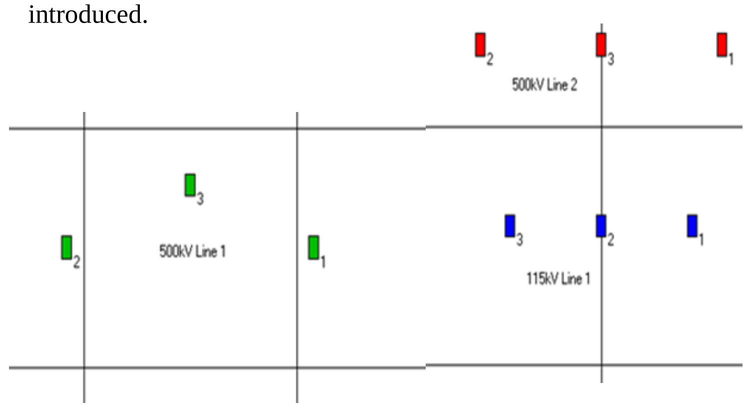

Figure 3 – Spatial arrangement of conductors for three transmission lines in a right-of-way [1].

Once all the parameters for every homogeneous section are gathered, the transmission line impedance calculations can be performed on each homogeneous section. The impedances of all homogeneous sections are then summed together to derive the impedance of the entire transmission line.

The traditional method is ideal for reducing the number of calculations required for the impedance of a single transmission line. This was critical when calculations were done by hand and by the first computer technology available. However, with the tremendous computer technology improvements over the past few decades, the need to reduce calculation numbers is no longer required. It is therefore possible to use new methods discussed next to improve transmission line impedances by reducing the limitations of the traditional method.

<u>Next-Gen Structure-to-Structure Method</u>

A new next generation method would no longer utilize homogeneous sections, but would instead calculate the impedance of every line segment between two structures. This would account for every build variation along an entire line, removing those errors from the traditional method results.

For this method, every parameter that is required for each homogeneous section in the traditional method must now be required for each individual tower structure along an entire transmission line. This is a tremendous more amount of data over the traditional method, and while there are computer technologies that can process this data, it is still not realistic to require designers and engineers to manually enter this data into a program. This data for all structures must therefore be in a digital format for automatic consumption by software applications. Fortunately, the NERC and its reliability standards have created new activity that provides this information for this next generation method.

Due to the NERC Standards that involve transmission lines, such as those in the facilities (FAC) group, many transmission line owners have turned to new modeling techniques to meet the reliability standards. Helicopters mounted with LIDAR is the most commonly used new technology to provide detailed 3D, geo-spatial information of everything inside and adjacent to transmission line right-of-ways. This information provides incredible snapshots of any vegetation or other type of encroachment into the transmission lines. Yet this new information also contains every parameter needed for the next generation structure-to-structure method, with pinpoint precision. When this LIDAR data is combined with new transmission line CAD applications, the result is a full set of digital data containing everything needed for transmission line impedances from structure to structure. Figures 4 and 5 provide examples of the new transmission line design models that are created with this data.

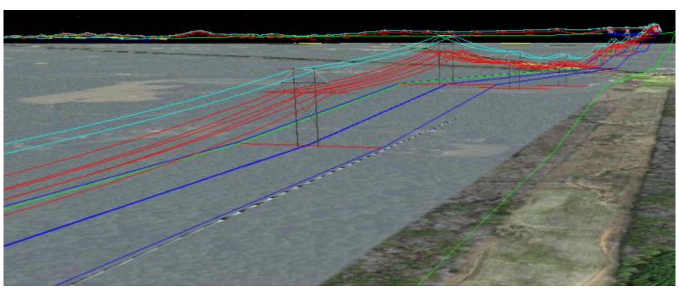

Figure 4 – Example of a next generation transmission line design model [4, 5, 6].

While this next generation structure-to-structure method removes errors from the homogeneous section method, the method does not account for changing soil resistivity over the length of a line or during a variety of weather conditions. This next generation method also does not account for changing sag length of energized conductors as ambient temperature changes.

The structure-to-structure method reduces line impedance errors from the traditional method by accounting for build variations along the length of a line and by providing precise parameters (ex: conductor spatial arrangement) over hand-calculations. As with everything in engineering, this improvement does come with a tradeoff. The amount of data and calculations increases tremendously when compared with the traditional method. Returning to the 65-mile 500kV line with 262 structures, the traditional method reduced the line into three homogeneous sections. With the next generation method, all 262 towers need to be modeled in the same detail as the three homogeneous sections in the traditional method. It is unrealistic to manually model lines with the structure-to-structure method. New software tools are required to extract the structure parameters for every individual structure and import the data into impedance calculators. Unfortunately these tools are not available at the time of this writing, but the author is working with various vendors of new transmission line CAD applications and impedance calculator programs to find a solution. It is the author's belief that this next generation structure-to-structure method is critical to reducing errors inherent with the traditional method.

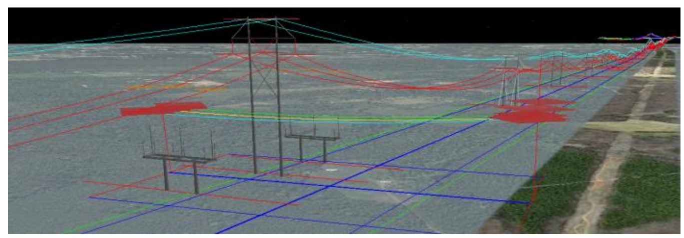

Figure 5 – Example of a line model showing tower changes at a load tap point on the line [4, 5, 6].

<u>Offline Method</u>

After a transmission line has been built, an offline method can be used to measure the impedance of the line. This method requires the line be de-energized (offline) and isolated from the power grid, usually accomplished by opening breaker disconnect switches. While it is inconvenient to require the line be de-energized, this method can result in accurate impedances for the final build of a transmission line.

Once a transmission line is de-energized, this method requires one terminal of the transmission line to be grounded. The next step is to inject voltages and currents onto the line at the ungrounded terminal for each type of impedance measurement. The measured voltages and currents across the phase conductors (phase-phase, phase-ground, and three-phase) are used to calculate line impedance measurements. See Figure 6 for the layout of the offline method test setup.

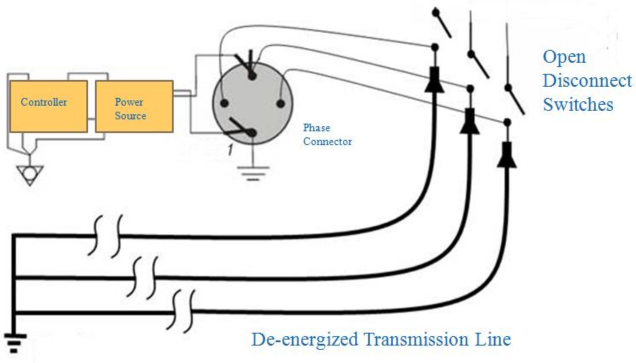

Figure 6 – Offline method test setup [7].

Dominion Virginia Power decided to use this offline method on two 230kV transmission lines. Dominion's System Operations Center detected voltage problems at one substation where two parallel 230kV underground transmission lines terminated. After a thorough investigation into the impedances of these two lines, major discrepancies were found between the manufacturer provided cable data and the actual field implementation of the cables. These discrepancies included operating temperature of the cables and ground continuity conductor configurations.

New impedance measurements were calculated and found to be drastically different from the original. Before making any production changes with the new impedances, it was decided to verify the line impedances using the offline method during a long construction outage of the two lines.

Figure 7 – Top left image is the test controller. Top right image is the phase connector unit. Bottom image is the power source for injecting voltages and currents [7].

Figure 8 – Underground transmission line terminal where impedance measurements were taken.

Figure 7 and Figure 8 show key elements of the offline method setup for one of the 230kV lines under test. At the completion of the test, the following total line impedances were calculated for one of the 230kV underground lines, and then compared with the original impedances based on the manufacturer's cable data.

<u>Offline Method Results</u>

Positive Sequence Z = Z1 = 0.106 + j0.991 Ohms
Zero Sequence Z = Z0 = 1.626 + j3.582 Ohms

<u>Original Impedances based on Manufacturer Data</u>

Positive Sequence Z = Z1 = 0.057 + j0.944 Ohms
Zero Sequence Z = Z0 = 0.837 + j8.927 Ohms

From the results, the original positive sequence resistance had an error of 46%, and the positive sequence reactance had 5% error. The zero sequence resistance had 48% error, and the zero sequence reactance had 150% error. These errors were very significant, but matched our expectations based on the discrepancies originally found concerning operating temperatures and ground continuity conductors.

<u>Correct Impedances Using Cable Impedance Program</u>

Positive Sequence Z = Z1 = 0.074 + j0.959 Ohms
Zero Sequence Z = Z0 = 1.631 + j3.760 Ohms

The corrected impedances using the cable impedance program were also compared with the offline method results. The correct positive sequence resistance had an error of 30%, and the positive sequence reactance had 3% error. The zero sequence resistance had 0.3% error, and the zero sequence reactance had 5% error. These results gave confidence that the cable impedance program is capable of providing fairly accurate results when the transmission lines are modeled correctly. However, the errors were still significant enough to warrant future tests with the offline method and other next generation methods.

Online Method

With time synchronized power system measurements, such as synchrophasors from Phasor Measurement Units (PMUs), it is possible to determine very accurate voltage and current phasors. By placing PMUs or other time synchronized equipment like Digital Fault Recorders (DFRs) at both terminal substations of a transmission line, the voltage and current phasors from these substations can be used to continuously calculate the actual impedance of the transmission line. This is the basis for the online method used to calculate the impedance of energized transmission lines.

From the common Pi equivalent model of a transmission line (Figure 9), the impedance of a line (R+jX) can be calculated using Equation 1.

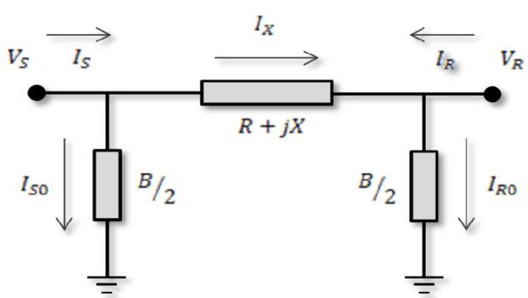

Figure 9 – The common Pi equivalent model of a transmission line.

$$\frac{V_S^2 - V_R^2}{I_S V_R - V_S I_R} = R + jX$$

Equation 1 – Impedance of a line from the Pi-model.

Dominion has a deployment of more than 80 PMUs on its 500kV network. From these 80 PMUs, 17 500kV transmission lines have PMUs on both substations. In 2013, one of those 500kV lines had an A-phase to Ground fault caused by a broken static wire located 17 miles from one of the substations. From the DFRs and relaying equipment monitoring this line, the double-ended fault location algorithm came up with a location of 11 miles from the same substation. This prompted an investigation into the impedance of this 500kV line. After a thorough analysis of the impedance using the traditional method, no problems were found. This led to a test using the positive sequence synchrophasor data from the PMUs on the terminals of this line.

After collecting synchrophasor data before and after the fault, Equation 1 was used on the data to calculate the positive sequence impedance. The results are shown below.

Original Impedance from Traditional Method
Positive Sequence Z = Z1 = 1.8362 + j38.28 Ohms

New Impedance from Synchrophasor Data
Positive Sequence Z = Z1 = 3.663 + j39.42 Ohms

From the synchrophasor data, the original positive sequence resistance was almost 50% off from the calculated resistance using synchrophasor data. The original positive sequence reactance, however, was less than 3% off from the calculated reactance using synchrophasor data.

For the same A-Ground fault on this 500kV line, the new impedance from synchrophasors was implemented into the double-ended fault location algorithm. This produced a new location of 14 miles from the same substation, an improvement of 3 miles closer to the actual fault location from the original location calculated. By using the same online method to calculate the zero sequence impedance of the transmission line, the expectation is to get even more accurate line impedances, and therefore even more accurate fault locations and other application results. With these good results, the online method will be used more frequently to monitor transmission line impedances over time and varying weather conditions.

Conclusion

With the demands of today's modern power systems, traditional line impedance methods may not be accurate enough. New line impedance methods include next generation structure-to-structure models, offline methods for de-energized lines, and online methods for continuous monitoring of line impedance. Most of these methods are available today with new technologies like synchrophasors, however some software applications are needed to assist in the detailed modeling required by new methods.

Dominion has had initial success with these new line impedance methods, and continued work in this area will allow for more improvements across all applications. A combination of the new line impedance methods will be required to improve power system applications that are critical for the reliability of today's power systems.

Biography

Kyle Thomas received his M.S. degree in Electrical Engineering from Virginia Tech in 2011 and is currently pursuing his Ph.D. while working for Dominion's Electric Transmission Reliability group. He has technical expertise in power system protection, automation, control, wide-area measurements, and fault analysis. Kyle is a technical lead of Dominion's synchrophasor installations, applications, and training, and is actively involved in the North American Synchrophasor Initiative (NASPI) and IEEE organizations.

References

1. Screenshots from the ASPEN Line Constants Software. http://www.aspeninc.com/web/index.html

2. "Step and Touch Potential Awareness", Volume 16 Issue 3, Utility Products. http://www.utilityproducts.com/articles/print/volume-16/issue-3/product-focus/safety-products/step-and-touch-potential-awareness.html

3. NERC Reliability Standards. http://www.nerc.com/pa/stand/Pages/ReliabilityStandardsUnitedStates.aspx

4. LIDAR – Light Detection and Ranging. http://oceanservice.noaa.gov/facts/lidar.html

5. Screenshots from the PLS-CADD Software. http://www.powline.com/products/pls_cadd.html

6. Screenshots from Google Earth Software. http://www.google.com/earth/

7. Omicron Transmission Line Test Equipment. https://www.omicron.at/en/products/all/primary-testing-diagnostics/cpc-100/