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Advancement in Transmission Line Impedance Calculations

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SUMMARY

This paper establishes the importance of transmission line impedance and subsequently discusses various methods of transmission line impedance calculations which are commonly used in the electric power industry. These approaches include the traditional method of calculation which assumes a transmission line as a combination of homogeneous sections and then calculates impedance for each section, another offline method which makes use of line testing equipment and an online method which employs synchrophasor data for continuous monitoring of line impedance values. More importantly, this paper presents an innovative Next-Generation method for finding out impedance values. The corresponding trade-offs for each method has been discussed as well.

KEYWORDS

Transmission lines
Mutual Impedance
Zero Sequence Impedance
Conductor spatial configuration
ROW-Right-Of-Way
3D CADD modelling
LiDAR- Light Detection and Ranging
PMU- Phasor Measurement Unit

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Background

Transmission of electric power occurs through overhead and underground transmission lines. These transmission lines are significant system elements as they connect the Generation and Distribution parts of the power system. The planning & operation of any power system requires a variety of studies and analytics to be performed, so the system can be built and operated in a secure and cost-effective manner. Now, most of these studies and analytics require the transmission lines to be modelled in some way. For all kinds of electrical studies, transmission line models are defined by line parameters.

These line parameters are [1]:

- Series resistance: accounts for thermal losses in the conductor.
- Series inductance: accounts for effects of the magnetic field around the conductor.
- Shunt conductance: accounts for the leakage currents along the insulators and in the air.

These are the parameters that together form the total impedance of a transmission line.
To illustrate the importance of transmission line impedances, the figure below shows the different departments within Dominion Virginia Power (DVP) which require it for their various specific applications:

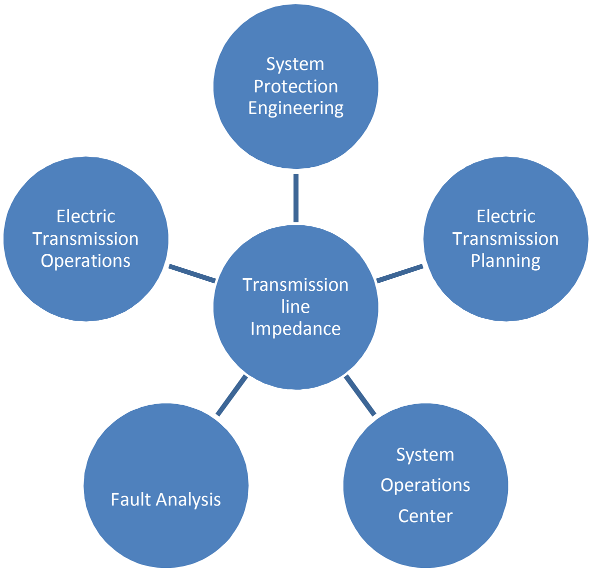


Figure 1: Departments within DVP's Electric Transmission which make use of Transmission Line impedance values.

Their specific applications include:

- System Protection Engineering: Protection studies, Relay settings etc.
- System Operations Center: SCADA/EMS models, ISO/RTO models, etc.
- Electric Transmission Operations: Running Simulation models, both Real-Time and Offline.
- Electric Transmission Planning: Building fault and planning models
- Fault Analysis: For configuring Digital Fault Recorders and General Metrics.

Motivation

As seen in the previous section, on account of its diverse vital uses, the importance of the transmission line impedance is well established. Hence, the point to be noted here is the accuracy and precision of the models, studies, and analytics, depend on the level of accuracy and precision of the transmission line impedance values [2]. So the calculation of these impedances should be as exact as possible.

To cite an example, at one point in time, the DVP System Operations Center was facing difficulties operating two 230kV underground transmission lines. It was found that due to an error from the wire manufacturer, a wrong value of impedance was entered into the network. DVP de-energized the line and conducted line tests which confirmed the manufacturer's wire data error.

Apart from these data errors, calculating the transmission line impedance is difficult and different from any other equipment in the transmission network because of the line's length, construction, environment and accessibility. Hence, they can often be inaccurate. To achieve the moving target of maximum accuracy, there are many methods of calculations prevalent in the electric power industry. All these methods and the various trade-offs with each will be discussed in the sections that follow.

Traditional Method: Method of Homogeneous sections

Transmission lines have existed ever since people decided to send power over long distances, and initially the existing computational power was inadequate to calculate very precise line impedances. Therefore, a method which required fewer calculations per transmission line was devised and since then this method has become the standard way of calculating impedances. This method involves two steps: The first step is to divide transmission lines into different homogeneous sections on the basis of similar physical, spatial and electrical characteristics. These characteristics include:

- Phase and static conductor spatial arrangement
- Phase and static conductor type with electrical parameters
- Static conductors segmented or not
- Bundled conductors
- Soil resistivity
- Conductor sag
- Voltage level
- Right-Of-Way

For example, as shown in Figure 2, the 263 structure transmission line is divided into three homogenous sections namely T-1, T-2 and T-3. This means all structures inside these sections are assumed to be exactly the same in regards to the aforementioned characteristics.

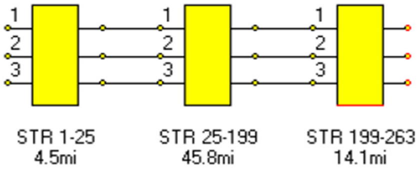


Figure 2 Homogeneous sections of a transmission line

Now, the second step is to calculate impedance of each section i.e. T-1, T-2 & T-3 and then add all of them together to find the impedance of the line. It is evident how the assumptions have reduced the calculations almost 10 fold. Hence, this is still the most widely used way to calculate impedances.

However, there are numerous problems associated with it. To reduce the computational effort, multiple simplification steps are taken which do not apply in practice. The assumption that every tower within a so-called "homogenous" section is exactly the same is most likely incorrect. The actual characteristics may change (however small) from tower to tower. The errors in recording the exact placement of transmission lines who share their Right-Of-Way (ROW) generate incorrect mutual impedances. Also, the whole process involves vigorous manual data entry and thus is highly prone to errors. As such, the line parameters calculated in this way are not precise.

To overcome these inadequacies, some other methods have been developed. Offline and Online are the two most popular methods amongst them.

1. Offline Method

This method requires the transmission line to be taken out of service and isolated from the grid via the action of circuit breakers and switches. After it is de-energized, one end of the transmission line is grounded and the other end is subjected to line testing equipment which are used to inject current and voltage into seven different loops. Three for each phase-phase loop, three for each phase-ground loop and one for the three phases connected parallel to the ground. Then voltage and current across the conductor are measured. From the measurement data of the different loops, line parameters are calculated [3].

The test setup is shown in the figure below as an example. [4]

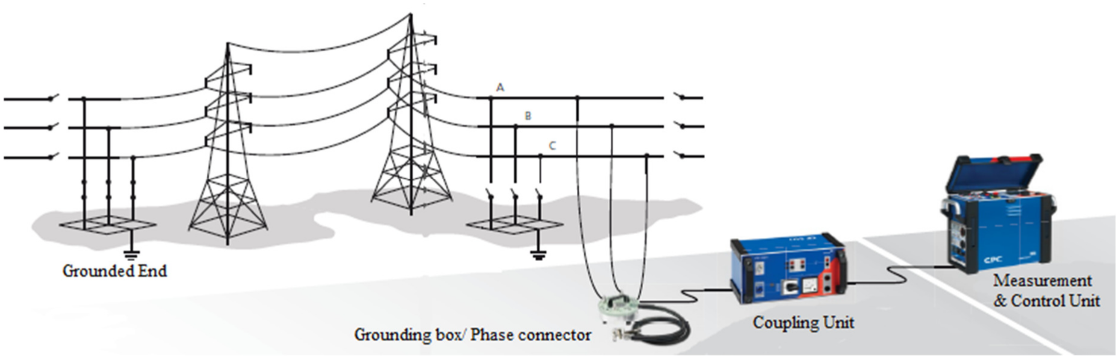


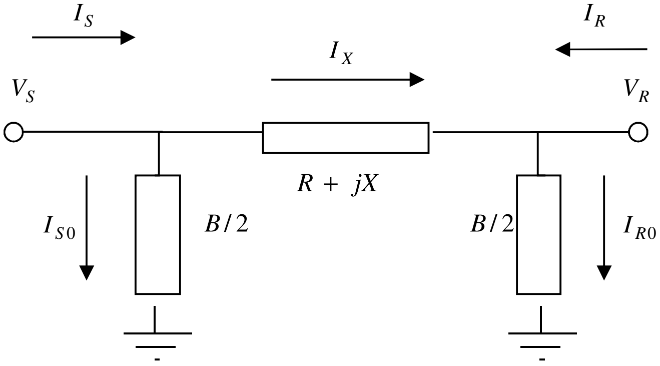
Figure 3 Offline Method Test Setup [4]

The measurement and control equipment shown in Figure 3 measures and records the value of voltage and current. To the left of that is the coupling unit, which facilitates the safe connection between the test system and the High Voltage (HV) cable. The equipment shown in the figure to the left of the coupling unit is the grounding box, which physically connects the coupling unit to the cable. Generally these phase connectors also contain surge arrestors to ensure safe testing during unexpected events. [4].

This method produces very accurate results but it requires the line to be isolated from the grid, which is not always a possibility due to system reliability demands and chances of real-time operation contingencies.

2. Online Method

This method is carried out by employing high fidelity equipment known as Phasor Measurement Units (PMUs) at both ends of transmission line substations. These PMUs are able to give time synchronized power system measurements of voltage and current (known as synchrophasors) at both ends. The basic idea behind the whole setup is since the transmission line length is considerably high, admittance Y of the network does play a role in calculating the effective circuit parameters, unlike in the case of short transmission lines. For this reason the modelling of longer transmission line is done using lumped shunt admittance along with the lumped impedance in series to the circuit called as a pi-equivalent circuit (because it looks like the Greek letter π). For a transmission line with impedance $Z = R + jX$, the transmission line is modelled as shown below where V_S is the sending side voltage, I_S is the sent current whereas V_R is the receiving end voltage & I_R is the current received at the other end. The impedance can be calculated using suitable mathematical equations shown below:



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

Figure 4 PI equivalent model of a transmission line

The Online method has been so named because the transmission line impedance is calculated and monitored continuously while it is in-service. This goes further to establish its importance as it calculates impedance in real time rather than a one-time measurement when the line has to be de-energized. De-energization costs a lot of money (among various other problems) to utilities and is not recommended. This method would guarantee the most accurate value (as of now) of impedances among the methods discussed. But, there is still time before this method becomes a normal routine as PMUs continue to get deployed across transmission grids.

A new method is still necessary to calculate line impedances before a line is energized; one that reduces assumptions and optimizes computational power and efficiency available today. This is where the proposed Next-Gen Method comes into picture.

Proposed Next-Gen Method to calculate Transmission Line Impedances:

As discussed before, the traditional method of calculation was focused on decreasing the computational effort and data. This was so because the computational power originally available was nowhere as capable as it is today, and hence, the assumptions and simplifications were incorporated.
Since we have powerful computers today, this trade-off is no longer required. Therefore, a new method is proposed which removes these assumptions by removing the concept of homogenous sections and instead calculates the impedance for each span of wire between two towers. The methodology that goes behind this idea is explained as follows.

The North American Electric Reliability Corporation (NERC) issued the FAC 003 alert to all U.S. and Canadian utilities requiring regular monitoring of the continent's 450,000 miles of transmission lines and their Right-Of-Ways (ROWs) for vegetation encroachment and line rating assessment with effect from 11 July 2014 [5]. This mandated line monitoring was typically completed via airborne LiDAR (Light Detection and Ranging) technology.

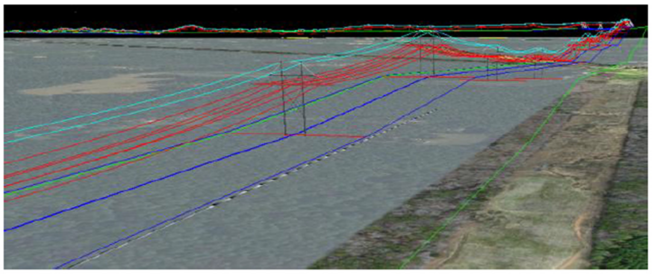


Figure 5 Transmission lines mapped via LiDAR

LiDAR was used to map all the DVP transmission lines, and this data was processed with suitable 3D CADD software and hence comprehensive models, vegetation reports and line monitoring reports were created.

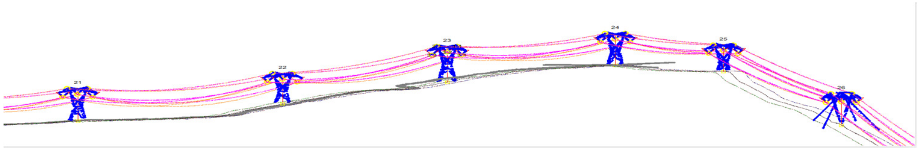


Figure 6 3D section of a comprehensive 3D CADD model

As shown in Figure 6, the comprehensive models created can be used to get GPS coordinates of static and phase conductors on the line and consequently their spatial configuration. The information about conductor types, line length, conductor sag, number of wires per phase, etc. is present in 3D CADD software as well. Therefore, the combination of LiDAR and 3D CADD software create a software model of a transmission line that contains all required information for line impedance calculations.

Through prudent calculations and meaningful manipulation of data via the software tools, all the information that was previously required for each homogenous section, can now be automatically extracted for every tower instead. This data is now used to mathematically calculate the impedance using the commonly available Line Constants software program. After calculating the impedance for every span of wire between two towers, all span impedances are summed to evaluate the impedance of the entire transmission line.

Results

A 500 kV transmission line within the DVP Electric Transmission network was chosen for the pilot project to show the proof of concept and the positive and zero sequence results were recorded.

Line Parameters	Traditional Method	Next-Gen Method	Percentage Difference (%)
Line Length	64.39 miles	64.50 miles	0.017
Positive Sequence Impedance (pu)	0.00073535 + j0.015319	0.00074060 + j0.013471	12.43
Zero Sequence Impedance (pu)	0.0075436 + 0.053445	0.0075621 + j0.058711	9.67

Both impedance values (Traditional method and Next-Gen method) for this 500kV line were then used in the fault location calculation using the Double-Ended algorithm for an actual A-phase to Ground fault. The fault location derived using the Next-Gen method was 17% closer to the actual fault location than the Traditional method. These results show that the Next-Gen Method can result in improved impedance accuracy by utilizing the technology available today, thus removing the assumptions to simplify impedance calculations as used in the traditional method.

Conclusion

Transmission lines are the lifelines of a power system and their protection and operation is of utmost significance. The different methods listed have the same aim, to achieve maximum accuracy of transmission line impedances. The proposed method aims to achieve this with the help of modern computer technology and software readily available by removing the various assumptions used in the traditional method to calculate line impedance. Further work is in progress to test additional DVP lines and compare the results.

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