Grounding Considerations for Transmission Line Protection

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Abstract — The purpose of this paper is to identify transmission line design and grounding configurations for which tower footing resistance may have a significant impact on resistive fault coverage requirements and warrant additional study. This paper reviews the fundamental concepts of tower grounding from a line relaying perspective and documents the relative impacts of tower grounding resistance. The apparent impedance of various overhead shield wire designs, the resulting fault current distribution among towers, and typical structure grounding approaches are addressed in this report. Apparent impedance calculations and simulations of typical transmission line grounding configurations will be presented.

I. INTRODUCTION

The most common transmission line faults involve a single-phase faulting to ground, often due to an insulator flashover. During a ground fault zero-sequence current flows into the system at the source and returns to the earth at the point where the system has faulted to ground. The flow of zero-sequence current is impeded by the line zero-sequence impedance, any arc resistance, and the impedance of the local connection to ground (tower footing resistance). The line zero-sequence impedance data is readily available. This leaves arc and footing resistance for consideration. There are several methods for estimating arc resistance that are commonly applied, but depending on the line design and geographic location, the tower grounding system will present a significant resistance. Both arc and tower footing impedance impact transmission line protection, lowering the available ground fault current and increasing the required resistive reach of distance based protection. While the tower footing resistance is often overlooked, it can be significant on specific line configurations. Identifying which lines will present a significant footing resistance, and obtaining a reasonable upper limit for this resistance, is relatively straight forward.

II. RESISTIVE REACH IN LINE PROTECTION

A. *Ground Fault Detection Methods*

Digital relays offer several methods for detecting ground faults. To further enhance the ability, or sensitivity, of the relay to detect ground faults these methods can be used in communications-aided tripping schemes. The most common methods for detecting ground faults are:

- Differential
- Directional Ground Overcurrent
- Directional Negative-Sequence Overcurrent
- Mho Ground Distance
- Quadrilateral Ground Distance

Ground and negative-sequence overcurrent elements can be non-directional if the application allows use of a non-directional element, for example, on a radial line. These overcurrent elements provide the best sensitivity for detecting high resistance faults on transmission systems [1].The sensitivity of these elements is simply limited by the pickup setting, the setting range of the relay, and the directional element. For the most part, and especially in communications-aided tripping schemes, these elements can be set to detect fault resistances in the hundreds of ohms.

Mho ground distance elements have a circular characteristic when plotted in the impedance plane and determine the impedance to the fault by comparing voltage and current signals. Figure 1 shows a steady-state mho characteristic. The mho element provides limited fault resistance coverage due to this circular characteristic.

Quadrilateral ground distance elements have a polygon-type characteristic that is determined by the manufacturer. Figure 2 shows a typical quadrilateral characteristic. These elements consist of three or four measurements that are combined into a single element. The three primary elements are: 1) a reactance measurement, 2) a resistive measurement, 3) a directional element. In some designs there are two resistive measurements; one for a right-hand resistive blinder and one for a left-hand resistive blinder.

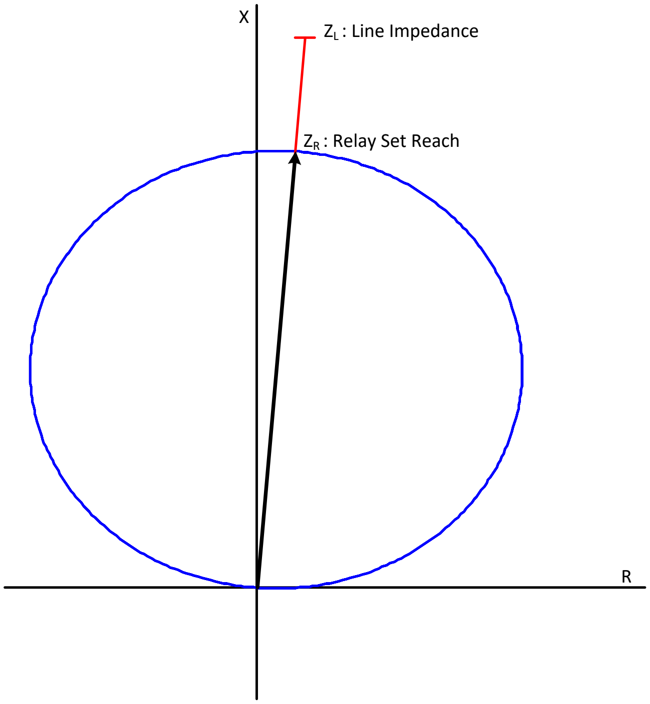

Figure 1: Steady-State Mho Characteristic

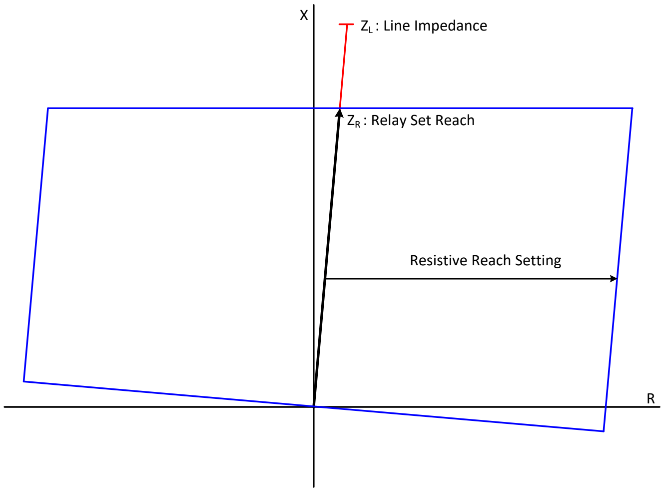

Figure 2: Typical Quadrilateral Distance Characteristic

Line current differential schemes provide the best ground fault sensitivity and security. This is because the scheme measures the current at the fault and not at each line terminal, as in the overcurrent or distance-based schemes. The amount of fault resistance coverage by a line current differential scheme is limited only by the relay setting range and the magnitude of load current on the protected line.

B. *Methods for dealing with increased fault resistance*

For the purposes in this paper this discussion focuses on distance elements as they are the most limited in detecting high resistance faults. The mho element, being the most limited, has little in the way of options for increasing the elements ability to detect high resistance faults. The adjustment the protection engineer can make is to increase the reach of the mho element. While this may be possible for an overreaching element, such as those used in a communications-aided scheme, unsupervised tripping elements are limited on the reach they can use. One design aspect of a mho element that may help increase the resistive fault coverage is what is known as the dynamic characteristic [2]. Using memory polarization in a mho element design results in the characteristic expanding back to the source behind the relay, see Figure 3. However, the duration of the expansion can be very short and the amount of expansion, being proportional to the source impedance, can be insignificant in systems with strong sources.

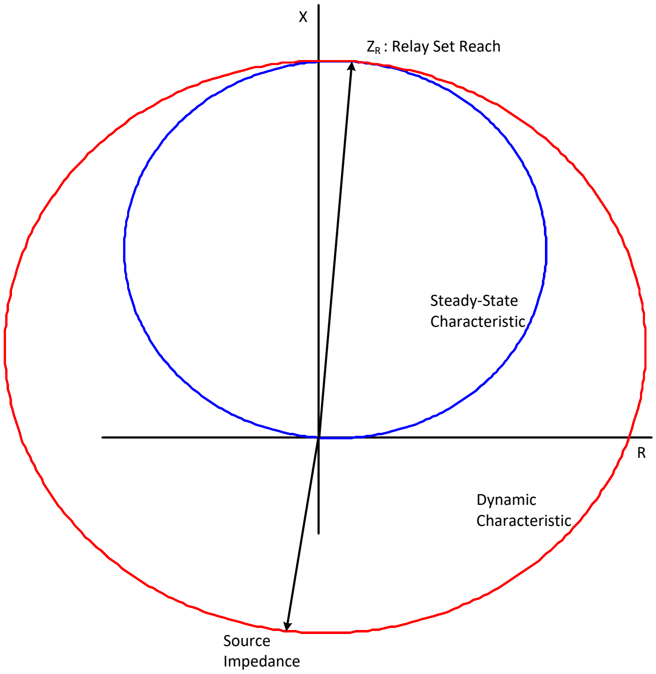

Figure 3: Dynamic Mho Characteristic

A quadrilateral element offers more flexibility in covering high resistance faults because the resistive reach can be set by the protection engineer. Although setting a large resistive reach would seem to be a good solution, it can also lead to other problems, especially on non-homogenous systems [1]. Caution should be used when considering large resistive reaches with quadrilateral distance elements, in particular, with direct tripping elements that are set to under reach the remote terminal, as overreach can be a problem.

C. *Sources of Ground fault resistance*

1) *Arc Resistance*

Many ground faults on transmission lines are a result of a flashover of the insulators. The resulting arc is resistive in nature. Two accepted methods for calculating the arc resistance are the empirically-derived Warrington and Westinghouse equations, which are shown in equations 1 and 2, respectively.

$$R_{arc} = \frac{8750*l}{I^{1.4}} \qquad (1)$$

$$R_{arc} = \frac{440*l}{I} \qquad (2)$$

Where:
R_{arc} is the arc resistance in Ohms
l is the arc length in feet
I is the current flowing through the arc in Amps
The arc length is typically assumed to be the length of the insulator. Table 1 provides a summary of arc resistance values calculated using each of the equations above, for various arc lengths and fault current magnitudes.

Table 1: Arc Resistances for 4 Foot and 8 Foot Arc Lengths

Fault Current (A)	4 Foot Arc Length		8 Foot Arc Length	
	Warrington Method (Ohms)	Westinghouse Method (Ohms)	Warrington Method (Ohms)	Westinghouse Method (Ohms)
1000	2.21	1.76	4.42	3.52
2000	0.84	0.88	1.67	1.76
5000	0.23	0.35	0.46	0.70
10000	0.09	0.18	0.18	0.35
20000	0.03	0.09	0.07	0.18

Note that the voltage drop across the arc remains constant according to the Westinghouse method, and decreases according to the Warrington method, as the fault current increases. Care must be taken when modelling arc resistance since it is not a constant value, particularly when accounting for infeed from a remote terminal. Other components of ground fault resistance, particularly the tower footing resistance and shield wire impedance, can be modelled as fixed values of impedance, and their apparent resistance will be affected by infeed from remote sources.

2) *Tower footing impedance*

An additional source of ground fault resistance is introduced by the tower grounding system. Ideally the transmission line tower would be perfectly grounded; in practice each tower grounding system will have some measurable impedance. This value is almost always resistive, though complex counterpoise grounding systems may introduce some reactive impedance. Tower footing resistances can range from less than 5 ohms to greater than 300 ohms based on a variety of factors. Often the tower footing impedance is specified by utility standard or various transmission line studies which will be discussed in subsequent sections of this paper.

III. GROUNDING FUNDAMENTALS

Grounding equipment and structures are commonplace and are important to many aspects of the electrical power industry. The goal of grounding design is to provide a solid, low impedance path to earth and is applied at generation sites, transmission/distribution lines, and substations. Grounding serves multiple purposes, including personnel protection during faults, facilitating proper equipment operation for steady state and faulted conditions, and providing surge/lightning protection.

A. *Earth resistivity*

1) *Soil resistivity*

The resistance to current flow provided by a volume of soil is described as the soils resistivity, expressed in ohm-meters. The soil resistivity varies depending on moisture, composition, and temperature. Clay or loamy soil can have a resistivity from less than 10 ohm-meter to greater than 50 ohm-meter; however, sandy and rocky soil may have resistivity over 3,000 ohm-meter. IEEE Std 81-2012 provides methods for measuring soil resistivity as well as procedures for measuring grounding systems of substations or tower footings.

2) *Impacts of resistivity on zero-sequence impedance*

The zero-sequence self and mutual impedance for a group of conductors with an earth return is, in part, a function of the earth resistivity. The relationship between the self and mutual zero-sequence impedance of a line and the resistivity of the earth can be shown in a modified version of Carson's equations, adapted to relate to zero-sequence quantities [3]:

$$Z0 = 3r_c + 0.00477f + j * 0.01397f * Log_{10}\frac{2160\sqrt{\frac{\rho}{f}}}{GMR} \quad (3)$$

$$Z0_M = 0.00477f + j * 0.01397f * Log_{10}\frac{2160\sqrt{\frac{\rho}{f}}}{GMD} \quad (4)$$

Where:
$3r_c$ is the resistance of one conductor for a three phase circuit
f is the system frequency
ρ is the resistivity in ohm-meters

From these equations we can see that the zero-sequence impedance is proportional to the log of the square root of the resistivity. For typical line parameters moving from 50 ohm-meters to 500 ohm-meters may only result in a 10-15% change in the line impedance per mile. For this reason, the common assumption of 100 ohm-meter uniform soil resistivity typically results in relatively small error in the overall zero-sequence impedance of a line. Knowledge of the predominate soil type in the region where a line is installed may allow for slightly better estimates of the soil resistivity. However, given the variability of the earth resistivity over the length of the line it can be difficult to accurately predict. For reference, Figure 4 shows the variability of soil resistivity nationwide. The resistivity can vary considerably from tower to tower.

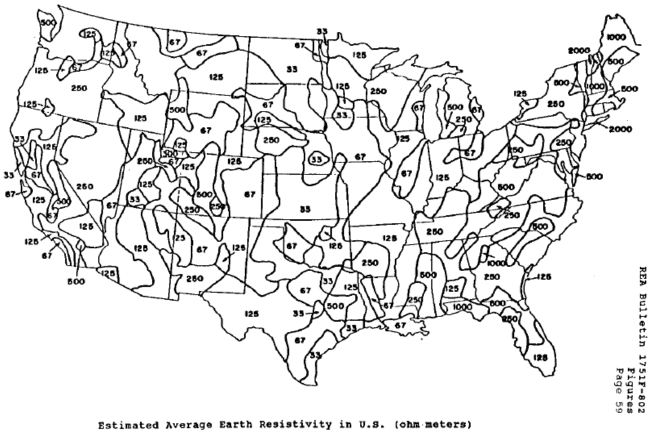

Figure 4: US Soil Resistivity Map

3) *Impact of Resistivity on Tower Footing Impedance*

When calculating the zero-sequence impedance of a line, the equations presented above assume that the zero-sequence path to ground is through a perfectly grounded conductor. In practice the tower grounding system will present some finite resistance to the current flow into the earth. The voltage drop across this impedance creates a local rise in ground potential.

Unlike the zero-sequence impedance of a transmission line, the impedance to earth (tower footing impedance) is directly proportional to the soil resistivity. As an example, the impedance of a single ground rod of length L, radius a, can be determined by the following equation from the EPRI Redbook [4].

$$R = \frac{\rho}{2\pi L}\left(log_e \frac{4L}{a} - 1\right) \qquad (5)$$

Where:

L is the length of the rod in meters

a is the area of the rod in square meters

This can be further expanded to account for additional ground rods, grounding conductor, the depth of the grid, and the mutual resistance between ground conductors. However, this simplified equation illustrates the principal that the soil resistivity will have a significant impact on the resistance to earth. Using the equation for a single ¾ inch ten-foot ground rod in 50 ohm-meter soil would present an approximately 22-ohm footing impedance, while the same rod in 100 ohm-meter soil would present approximately 44 ohm footing impedance, increasing in direct proportion to the soil resistivity.

B. *Tower Grounding*

Transmission tower grounding practices vary by utility and can be different from line to line or even structure to structure. The tower footing impedance is a major consideration for insulation coordination and from these studies it is typical to have a target footing resistance that should be reached at each tower. The RUS Design Manual of High Voltage Transmission Lines [5] recommends a footing resistance of 25 ohms or less in lightning prone areas to limit outages. Tower grounding typically consists of one or multiple ground rods, but may consist of horizontally buried conductor, described as counterpoise. The targeted resistance value is reached by measuring the resistance during installation and adding additional ground rods or counterpoise grounding as needed. Further details on this measurement process are outlined in IEEE Std. 81-2012. [6]

C. *Shield wire considerations*

Shield wires can impact the apparent impedance measured at the relay in two ways. First the zero-sequence impedance of the line is affected by the presence of shield wires, though the impact is often small enough to have little effect on protective relaying. Second, the presence of shield wires can also reduce the apparent tower footing impedance by providing multiple parallel paths through the shield wire and adjacent tower grounds for a portion of the fault current.

Shield wires can be continuous on all portions of a line, segmented, or simply omitted in the transmission line design. As a fault occurs on a line, the fault current will take all paths to return to earth. For a transmission line with shield wires, a fault at one structure could result in the majority of the fault current distributing to the adjacent towers extending from the faulted structure as shown in Figure 5.

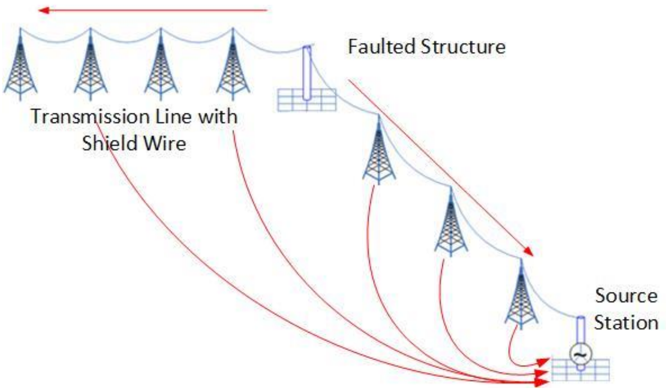

Figure 5: Ground Fault Current Distribution

When a line is installed without any shielding the worst-case impedance to earth seen by a protective relay would be the impedance of a single tower's grounding system. When a line is installed with a continuous and grounded shield wire, the fault current to earth can distribute via the shield wire to the other towers in the line and dramatically reduce the apparent impedance to earth.

Segmented shield wires may be installed to span only a couple miles before the continuity of the shield wire is intentionally broken. Each segment of the overhead shielding is grounded in only one place and should not represent a parallel path for ground fault current to distribute through. This is done on long EHV lines to reduce the losses associated with the induced current flow in shield wire. It's possible for the fault to flash over to the shield wire segment despite the insulation, though this is not a guarantee and predicting how many adjacent towers would be involved is difficult. On segmented lines the worst-case tower footing impedance would be that of a single tower, assuming the shield wire insulation is sufficient to prevent flashover on adjacent towers.

IV. ANALYSIS OF TRANSMISSION LINE GROUNDING

The analysis of a transmission line grounding system can become quite complex depending on the objective of the analysis. A simpler analysis may only require a couple soil layers and the tower grounding system configuration or specified structure impedance to determine adequate insulation. An analysis using sophisticated software may derive multi-layer soil models and include detailed modeling of each grounding conductor, shield wire, and conductor on the line as well as adjacent structures such as pipelines. This level of detail may be required for investigating the impacts of transmission line faults on an adjacent pipeline or railroad but is not practical for line protection studies. For line relaying, the primary concern will be obtaining a conservative estimate for the impedance seen by the relay, and less concern is given to any single tower.

On a line without grounded shield wires or any other path for the ground fault current to distribute through the impedance can be estimated directly from the target footing impedance required for insulation coordination. In many cases the tower grounding systems are measured during construction to ensure they meet or exceed the specified performance.

When an overhead shield wire is installed and grounded, the fault current distributes through multiple towers to ground resulting in reduced apparent impedance. The equivalent network for this connection is shown in Figure 6

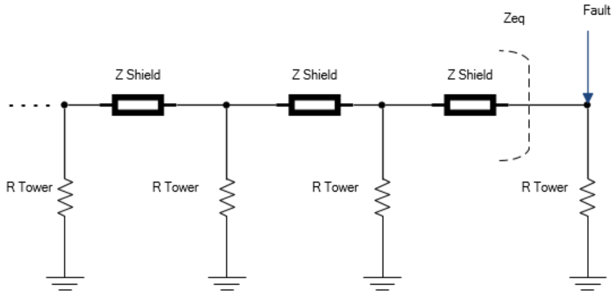

Figure 6: Infinite Half Line Ladder Network

The composite grounding system impedance can be determined by calculating the equivalent impedance of the ladder network as seen from the fault. Assuming equal impedance per span, Z_{Shield}, and equal tower grounding impedance, R_{Tower}, the equivalent impedance of the shield wire/tower network across the line can be found from equation (6) for an infinite half line in Enderyni's paper [7].

$$Zeq_{Line\ end} \approx \left(\frac{Z_{Shield}}{2} + \sqrt{Z_{Shield} \times R_{Tower}}\right) \qquad (6)$$

This impedance would be the equivalent impedance of the overhead system for a fault at the last tower on a radial line and the approximation holds for lines where the length of the line is greater than:

$$L_{min} > \frac{2 * L_{span}}{\sqrt{Z_{Shield}/R_{Tower}}} \qquad (7)$$

For most common shield wire and tower ground impedances the minimum length is between1 and 4 miles.

The tower footing resistance in this equation would be obtained from measured values, or more likely, assume all to be at or below the target footing resistance. The shield wire resistance and reactance values are readily available from reference books or in manufacturer published data [3] [4]. Note that these calculations use the self-impedance of the shield wires. For estimating purposes, the mutual impedances between the conductors can be neglected with minimal error [6] [8].

For midline faults that are at least the minimum distance of L_{min} from the local or remote stations, equation (8) is modified from the original version to account for fault current distribution in both directions from a given tower, reducing the apparent impedance to half of that calculated using equation (6) for faults that are more than a few spans from the station.

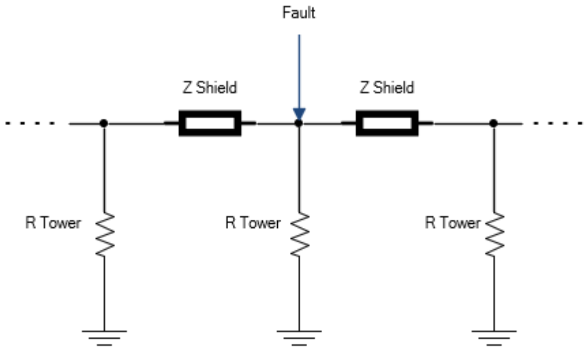

Figure 7: Midline fault with two directions for current distribution

$$Zeq_{Mid\ Line} \approx \frac{1}{2}\left(\frac{Z_{Shield}}{2} + \sqrt{Z_{Shield} \times R_{Tower}}\right) \qquad (8)$$

The change in the calculated equivalent impedance over the length of the line rises from the substation grid impedance to the calculated equivalent mid-line impedance as the fault location approaches a distance L_{min} away from the station. A rough approximation of this distribution is presented in Figure 8. On radial lines, faults near the end of the line will see a rise in apparent impedance as the number of towers available for current distribution decreases, eventually approaching 2 times the midline impedance. This radial scenario is effectively equivalent to the infinite half line shown in Figure 6, and therefore equation (6) applies.

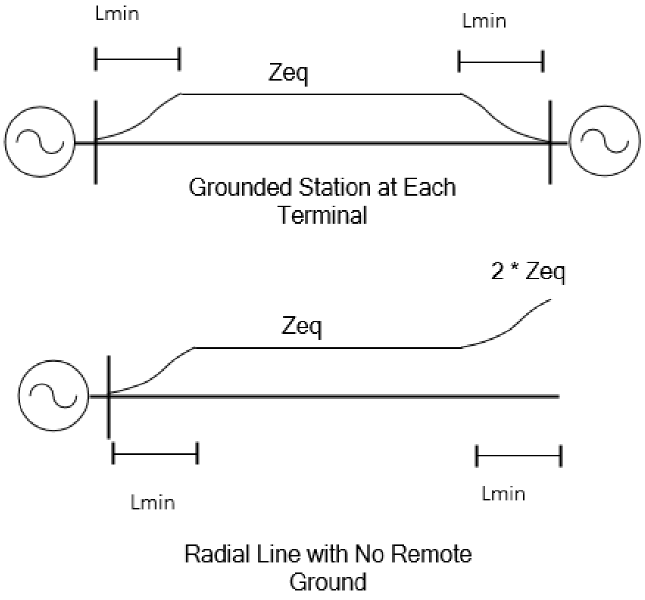

Figure 8: Change in equivalent impedance relative to fault location, Zeq is calculated using equation 6 in this document.

This simplified method of estimating the transmission line distributed impedance neglects the mutual impedances between conductors but has been shown to provide reasonable estimates of the distributed tower system impedance [6] [7] [8]. Once the distributed line impedance is known the equivalent impedance at the fault is the parallel of the faulted tower footing resistance and the equivalent distributed impedance.

$$Z_{apparent} = \frac{Zeq*R_{Tower}}{Zeq+R_{Tower}} \qquad (9)$$

Given the relation described in equation (9) above, in cases where $R_{Tower} >> Z_{Shield}$ the grounding system impedance will be significantly lower than that of any individual tower footing resistance.

Table 2: Impedances assuming 25-ohm footing, 750 ft spans.

Shield	3/8” EHS-AG	7#10 Alumoweld	AC-86/646 OPT-GW
Z Shield, (Ω/mi)	7.83+2.071j	4.73+0.777j	0.671+0.469j
R tower (Ω)	25	25	25
L span (feet)	750	750	750
Z Shield, (Ω/span)	1.112 +0.294j	0.672+0.11j	0.0953+0.067j
$L_{min,}$ (mi), Eq. 7	1.32	1.72	4.17
Zeq, (Ω/span), Eq. 8	2.95+0.425j	2.23+0.197j	0.837+0.273j
$Z_{apparent,}$ (Ω), Eq. 9	2.67	2.06	0.852

For reference, Table 2 shows the apparent impedances for 25-ohm tower footing resistance and various overhead shield wires on 750-foot spans. As indicated the apparent impedance is significantly lower than the tower footing impedance due to the parallel paths to ground represented by the overhead shield wire.

V. ANALYSIS AND RELAY ELEMENT RESPONSE

The Alternative Transients Program (ATP) was used to verify the apparent impedance given in equation (9) and [7]. The model uses a typical 230 kV vertical tower construction utilizing a single shield wire located at the top of the tower. Each tower span is modeled with a ruling span of 750 feet. The shield wire is modeled as a separate conductor so there are no mutuals to the line to match the estimation method used in [7] and [8]. The tower footing resistance is modeled as a resistor to true ground.

1) Validation of Zapparent and equivalent impedance

The shield wire conductors used in Table 2 and a tower footing resistance of 25 ohm were used in the ATP model. A single-line to ground fault was applied to the tower at a location beyond the Lmin value and the apparent impedance at the fault location were calculated. The results are shown in Table 3 and closely match the results show in Table 2.

Table 3: Zapparent from ATP Model

Shield	3/8” EHS-AG	7#10 Alumoweld	AC-86/646 OPT-GW
$Z_{apparent,}$ (Ω)	2.68	2.01	0.856

Figure 8 shows how the equivalent impedance changes with respect to fault location. Faults near the substation will have a reduced value of Zeq because the substation ground grid resistance to earth will dominate (assuming that it is much less than the tower footing and shield wire resistances).

Figure 9 provides some insight as to why faults near the substation have a lower Zeq value. The plot shows the distribution of ground fault current along the length of the line. This line was modeled with 3/8-inch EHS-AG overhead shield wire and has an estimated L_{min} of approximately 1.3 miles. It is apparent from this distribution that beyond the 1.3 mile mark any additional line length would play a very minimal role in the current distribution and resulting apparent impedance.

If the fault is less than the Lmin value from the substation, the majority of the current is shunted through the substation ground grid and not the towers. If the remote end of the line is not connected to the substation ground grid, the remote impedance is infinite, and the tower footing resistance will tend to dominate for faults near the end of the line (less than Lmin). For looped lines, the remote substation ground grid resistance will dominate for faults near that terminal.

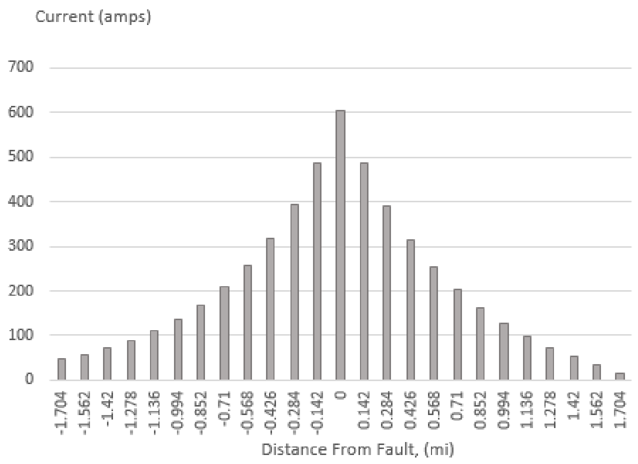

Figure 9: Current Distribution over 3/8-inch EHS shield wire with 25 ohm footing resistance. L_{min} *of 1.3 miles.*

Faults were taken near the line ends and at the midpoint for a shield wire that is ungrounded at the remote end and one that is grounded at the remote end. The 3/8” EHS-AG shield wire and a substation ground grid resistance of 0.1 Ω are used in the model. Figure 10 shows the result.

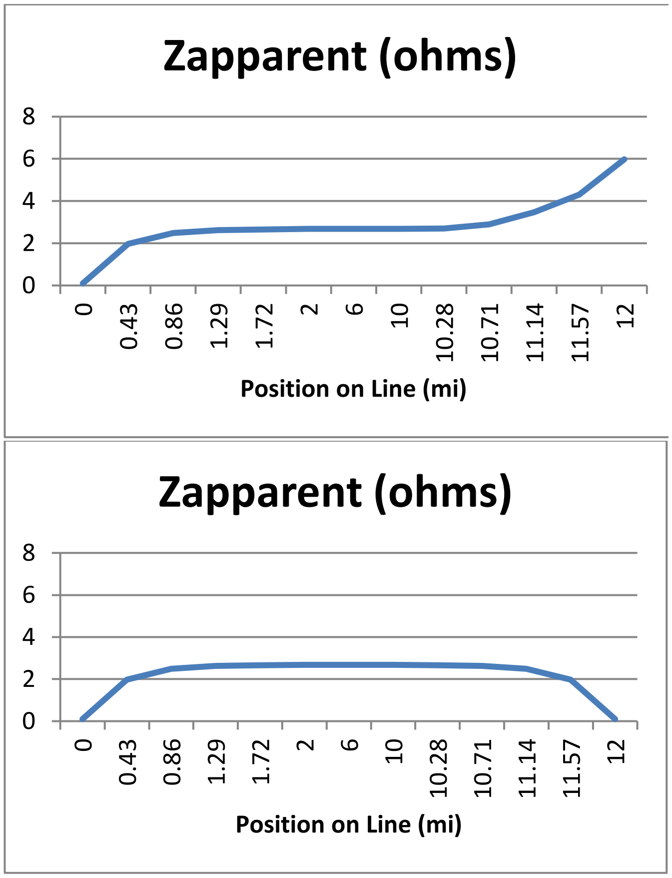

Figure 10: Zapp for no remote ground connection (top) and a remote ground connection (bottom)

The simplified method for calculating the tower and shield wire apparent impedance ignores the mutual coupling between the shield wire and the phase conductors. The shield wire is included in the ATP line model so that the effect of mutual coupling on Zapparent can be evaluated. Fault currents are varied from 2,500 amps to 25,000 amps to determine if mutual coupling affects from high fault had any impact. Results from the ATP model showed less than 5% difference in Zapparent when compared to the model with no mutual coupling.

2) *Effect of tower and shield resistance on relay elements*

The apparent impedance represented by the tower footing and shield wire resistance can have a significant impact on protective relaying. The impact would be greatest for distance-based schemes, especially those using mho elements, on short lines or where the shield wire or tower footings have high resistive values.

Figure 11 shows the apparent impedances measured by a distance relay on a 12-mile line using 3/8” EHS-AG shield wire. The plot shows the apparent impedance measured for a mid-line fault in a radial configuration (source at one terminal only) and tower footing resistances of 5, 25, 50 and 200 ohms. The mho circle represents a Zone 1 distance element set to 80% of the line impedance. In this case an under reaching mho element would cover mid-line faults for all tower footing resistances except the 200-ohm resistance.

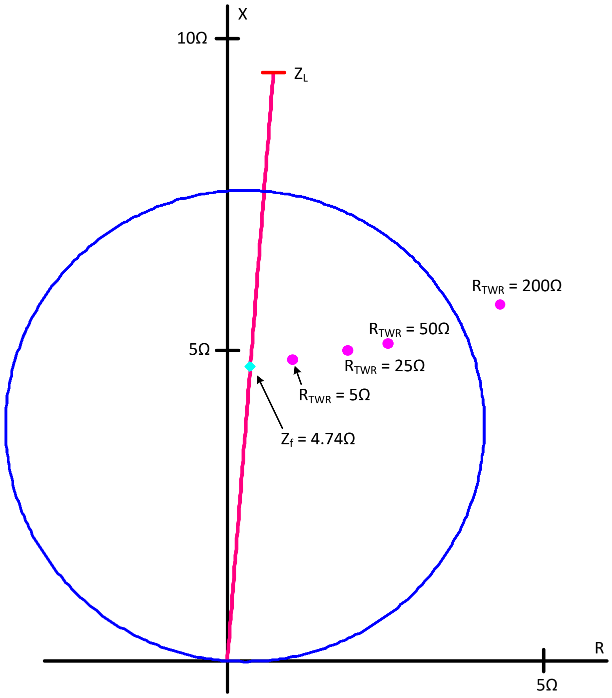

Figure 11: Apparent impedance seen by a distance relay for varying tower footing resistances

Figure 12 shows the same plot for a 4 mile line. For this example, the mid-line fault is covered for a 5 ohm tower footing resistance but not for the 25 or 50 ohm tower footing resistance. In this case the use of a quadrilateral ground distance element would be beneficial.

Referring to Figure 10, when the shield wire is solidly grounded to the substation ground grid at both ends, the apparent impedance is greatly reduced as the fault gets closer to the station. Because of this characteristic, overreaching elements used in communications-aided tripping schemes would be less susceptible to the increased impedance due to the shield wire and tower footing resistance.

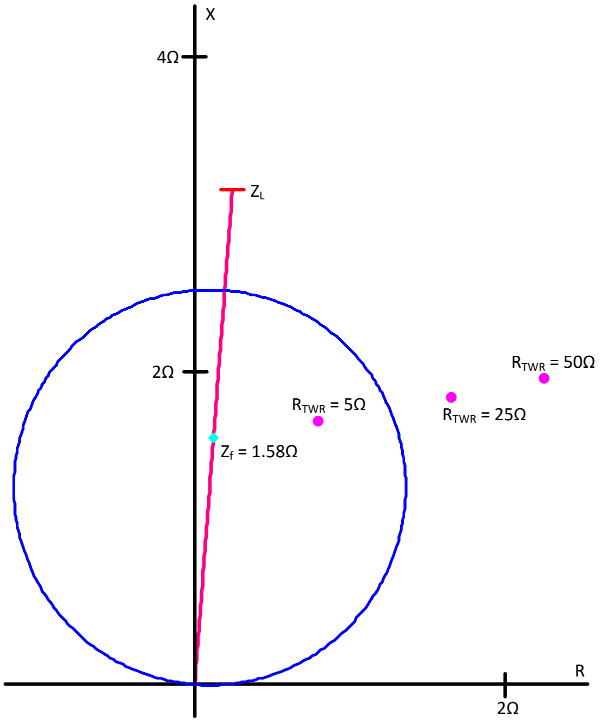

Figure 12: Apparent impedances for short line

Most transmission lines are looped (i.e., sources at both line terminals) and the fault current contribution from the remote terminal can impact the apparent impedance seen by the local relay. Figure 13 shows the apparent impedance plot for the same configuration as Figure 11 but with a source added at the remote terminal. The point Z_{RADIAL} is plotted as a reference. The points Z_{EQUAL} and Z_{2X} show the apparent impedance with equal sources at each terminal and with remote source equal to one-half the local source impedance (i.e., remote source contributes twice as much fault current).

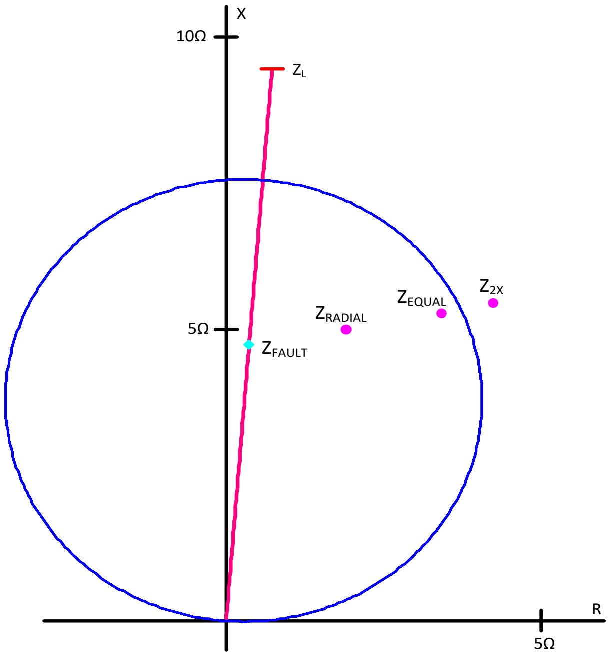

Figure 13: Apparent impedances with sources at both line terminals

As expected, the infeed from the remote source increases the apparent impedance to the point where it will be outside the mho element characteristic. Unlike arc resistance, where the value of the arc resistance is a function of the current magnitude at the fault, the combined resistance of the shield wire and tower footing is a fixed value independent of the fault current magnitude. In our example, the calculated arc resistance is 0.5Ω for the radial configuration and 0.1Ω when the remote source is two times the local source but the Zequivalent is the same for all conditions.

3) Determine the impact of shield wires and tower grounding to protective relaying

Most short circuit programs allow the user to input an impedance value for ground faults representing the fault impedance. The apparent impedance represented by the shield wire and the tower footings is calculated using equations (8) and (9). The result from equation (9) is then entered into the short circuit program as the fault impedance. This value does not vary based upon fault current magnitude and a fixed value can be used to test different fault locations for the relay response. As the fault gets closer to the substation (less than Lmin distance away), the apparent impedance is reduced as shown in Figure 10.

VI. CONCLUSIONS

A. Configurations where system grounding can impact line protection

Tower footing resistance can have a significant impact on transmission relaying. Assessing whether or not a particular line may have significant apparent fault impedance involves applying simple calculations to estimate the equivalent impedance to earth of the faulted tower footing resistance in parallel with the equivalent impedance of any overhead shielding.

1) No Shield Wires

Lines with no overhead shield wires or other metallic return can be expected to present a fault resistance equivalent to the tower footing impedance of a single tower, in some instances this value can be 300 Ω or more [9]. The value may vary from tower to tower, but each tower should be below the target footing impedance required for insulation coordination. Without a target footing impedance an approximation for the tower ground impedance can be calculated based on the soil resistivity and the installed ground conductor geometry; more detail on these methods can be found in references [6] [4].

2) Continuous Shield Wire

Installations with continuous shield wires benefit from significant fault current distribution. The ground fault current distributes via the shield wire taking multiple parallel paths to ground, significantly reducing the apparent fault impedance. The equivalent network for this fault distribution is shown in Figure 7 for faults located a few miles into the line. A conservative estimate for the apparent fault impedance represented by the tower/shield wire system can be obtained using equation (8) for most fault cases. Line end faults on radial lines with no remote grounding system would present a worse case apparent impedance of double that obtained using equation (8).

3) Other Shield Configurations

Aside from no-shield or continuous shielding some lines may have shield wires installed that have been intentionally segmented. In this case the fault current distribution is less reliable and changes if a fault results in a flashover between shield wire segments, and if so, for how many towers. The conservative approach would be to assume no fault current distribution unless it can be determined from the insulation studies that a flashover is likely.

Any other deviation from continuous shielding should be assessed on a case by case basis. For example, continuous shielding that is interrupted due to a line crossing may still provide significant current distribution provided it is grounded at each tower, and the uninterrupted sections meet the minimum length calculated by equation (7).

B. Impact on Protective Relaying

The impedance added by the shield wire and tower footing resistance can have an impact on the transmission line protection. Since impedance faults relate directly to decreased fault currents, both impedance and current based elements should be evaluated. The most susceptible are mho distance schemes where the resistive fault coverage is limited due the circular characteristic. The paper presents a simple method for determining the apparent impedance seen by the combined shield wire and tower footing resistances. Shield wire data is readily available and easy to obtain. The tower footing resistance may be more difficult to obtain but using a standard design value or even a worst-case estimate will provide the information required to evaluate the impact.

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VIII. BIOGRAPHIES

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