Personnel Grounding and Safety: Issues and Solutions Related to Servicing Optical Fiber Telecommunication Circuits in Optical Ground Wire (OPGW)

Final Project Report

Power Systems Engineering Research Center

Power Systems Engineering Research Center

Personnel Grounding and Safety Issues/Solutions Related to Servicing Optical Fiber Telecommunication Circuits in Optical Ground Wire (OPGW)

Final Project Report

Project Team

Richard G. Olsen
Washington State University

Sakis Meliopoulos
Georgia Institute of Technology

George Karady
Arizona State University

October 2002

Information about this Project

For information about this project contact:

R. G. Olsen
Professor
Washington State University
School of Electrical Engineering and Computer Science
P.O. Box 875706
Pullman, WA 99164-2752
Phone: 509 335 4950
Fax: 509 335 3818
Email: olsen@wsu.edu

Power Systems Engineering Research Center

This is a project report from the Power Systems Engineering Research Center (PSERC). PSERC is a multi-university Center conducting research on challenges facing a restructuring electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website: http://www.pserc.wisc.edu.

For additional information, contact:

Power Systems Engineering Research Center
Cornell University
428 Phillips Hall
Ithaca, New York 14853
Phone: 607-255-5601
Fax: 607-255-8871

Notice Concerning Copyright Material

ACKNOWLEDGEMENTS

EXECUTIVE SUMMARY

It is increasingly common to find optical fibers for telecommunication systems located inside ground wires on high voltage transmission lines. Cables that consist of optical fiber surrounded by ground wires are called optical ground wires (OPGW). In the course of installing and maintaining telecommunications equipment on optical fiber circuits, it is necessary for workers to have access to these cables. This access is facilitated by leaving excess cable on towers where equipment boxes are located so that the equipment and cable ends can be lowered to the ground where maintenance is performed in trucks or tents.

It is desirable to perform maintenance while the transmission line is energized. Given this, worker safety is a very important issue for the following reason. The OPGW cable is bonded to the tower and hence always at the same electrical potential as the tower. Under normal operation, very little current passes through the tower ground. Since tower grounding resistances are usually on the order of 10 - 100 ohms, there is little potential difference between the cable and the ground and it is safe to work on the cable. In case of either a fault or a lightning strike, however, the situation is different. It is possible in either case that the tower (and hence cable) potential may be significantly greater than that of the earth where the work is carried out. This means that workers may be exposed to unsafe conditions.

In this project, a study has been made of the voltages and currents to which workers are exposed while performing OPGW maintenance on or near energized transmission lines during fault conditions. The technique used for modeling this problem was first validated by comparing simulations with measurements performed during a bolted fault test by the U.S. Bureau of Reclamation (USBoR) and the Western Area Power Administration (WAPA). Once validated, the model was used to simulate typical situations that might be encountered during maintenance of OPGW while either the line being maintained or a nearby line is energized.

It has been found that unless special measures are taken to protect workers, they may be exposed to dangerous levels of voltage and current during a fault. This conclusion is true even if the work is being performed on a de-energized line that is parallel to an energized line on which a fault occurs.

Although not specifically evaluated as part of this project, one solution to the problem is the installation of a temporary ground mat underneath the work area. By bonding the OPGW and the truck or tent in which the maintenance work is being performed to this mat, the voltage and current levels to which workers are exposed during fault conditions are significantly reduced. This reduction occurs because a low resistance bypass is provided for the fault current that flows through the OPGW to the earth.

TABLE OF CONTENTS

1

INTRODUCTION

It is increasingly common to find optical fibers for telecommunication systems located inside ground wires on high voltage transmission lines. Ground wires that contain these fibers are called optical ground wires (OPGW). In the course of maintaining these telecommunications circuits, it is necessary for workers to have access to the fibers. This access is facilitated by leaving excess OPGW on towers where equipment boxes are located so that the equipment and cable ends can be lowered to the ground and maintenance performed in a clean environment. An example of a fiber maintenance operation is shown in Fig. 1. Here, the excess OPGW is brought to the ground and splicing is performed in the truck as shown.

Fig. 1 Maintenance of optical fiber that is inside a ground wire

Ideally, maintenance should be performed while the transmission line is de-energized. However, because the capacity of transmission systems has not increased as rapidly as the demand for electricity, it is now much more difficult to obtain permission to de-energize transmission lines in order to perform maintenance. Thus, maintenance is often conducted while the system is energized. Given this, worker safety is a very important

issue because the OPGW is bonded to the tower (hence always at the same electrical potential as the tower) while the work area may be at a different potential. Under normal operation (i.e. balanced three phase voltages), very little current passes through the tower ground. Since tower grounding resistances are usually on the order of 10 - 100 ohms, there is little voltage between the OPGW and the ground where the work is done and it is usually safe to work on the optical fiber. In case of either a fault or a lightning strike, however, the situation is different since a significant amount of current may pass through the tower ground that creates a ground potential rise (GPR). The tower (and hence the OPGW) potential may thus be significantly greater than that of the earth where the work is carried out. This means that workers may be exposed to unsafe conditions. This problem is described here as a "transferred potential" problem since the tower potential is "transferred" to the work area by the OPGW.

In this report, a study to simulate the voltages and currents to which OPGW maintenance workers are exposed and to identify measures that can be taken to insure the safety of personnel who work on OPGW cables during faults or lightning strikes is summarized. A result of this project will be the development of a rationale for procedures to safely maintain OPGW while the transmission line is energized.

The first part of the report is a summary of an effort to experimentally validate the modeling procedures used for the study. This is necessary to be certain that the numerous assumptions (e.g. homogeneous flat earth, linearity of the soil, number of flashed over ground wire insulators and quasi-state state conditions) made in the model accurately reflect the actual physics of the problem under fault conditions. The validation was accomplished by modeling a bolted fault test performed by the US Bureau of Reclamation (USBoR) and the Western Area Power Administration (WAPA) and comparing the simulated and measured results. The second part of the report is a summary of several simulations designed to predict the currents to which a worker would be exposed if maintaining fiber under potentially dangerous fault conditions. Of specific interest is the calculation of transferred potentials (i.e. the tower potentials that are "transferred" to the work area by the OPGW) and the currents induced in a person who simultaneously touches both the OPGW and the work area ground during these fault conditions. An examination of these results leads to recommendations for safe work practices.

2

MODEL VALIDATION USING A BOLTED FAULT TEST

2.1 Rationale for Validating the Model

Modeling of this problem is a two-step process. First, the real physical problem for calculating the transferred potentials is approximated by a physical model that is idealized enough to allow tractable mathematical solution. A number of approximations are made when developing this model. These include linearity of the earth, a single layer of homogeneous flat earth, horizontal transmission line conductors, identical grounding electrodes at each tower and a fixed number of zero impedance ground wire insulator flashover impedances (if insulated OPGW is used). As mentioned above, these approximations are made in order to allow reasonably economical solutions to the problem. Another reason for this is that there is generally only limited information available about the physical problem to be modeled. In this case, a more complex model could not be constructed. Although the mathematical solution to the idealized problem can be found quickly and accurately, the final results are suspect due to the above-mentioned approximations. Second, an equivalent circuit (for the power line) and fields (for the ground currents) model is found and solved mathematically using a number of low frequency approximations. These include ignoring displacement currents in the earth and the use of the quasi-static approximation. Although the solution to the latter model can, again, be found quickly and accurately, it is suspect due to the approximation made in both steps. For this reason, there will be more confidence in the results if the modeling methods used here are compared to an experiment similar to the cases directly applicable to the OPGW maintenance problem of concern here.

To validate the modeling procedures for this project, then, a model has been constructed to compare with the results of the experiment described in [1]. In this work, a bolted fault test was conducted on WAPA's Mead-Perkins 500 kV transmission lines near Boulder City, Nevada. The magnitude of the fault currents is on the order of that expected for typical OPGW transferred potential problems. Thus, if the comparison is successful, one can have more confidence in the results presented later on the safety of OPGW maintenance during faults.

2.2 Description of the Bolted Fault Test

The bolted fault test was conducted approximately one mile from the Mead Substation. At that point, the transmission line is configured horizontally with the cross sectional geometry shown in Fig. 2. The phase conductors were at a height of 80 feet above ground and spaced 20 feet apart. The two ground wires (OPGW in this case) are at a height of 100.7 feet and are also spaced 20 feet apart. Each of the phase conductors is

Joree and has a DC resistance per unit length of 0.0371 Ω/mile and a diameter of 1.88 inches. Each of the ground wires has a DC resistance per unit length of 1.658 Ω/mile and a diameter of 0.36 inches. The earth was assumed to have a resistivity of 100 Ω-meters as shown.
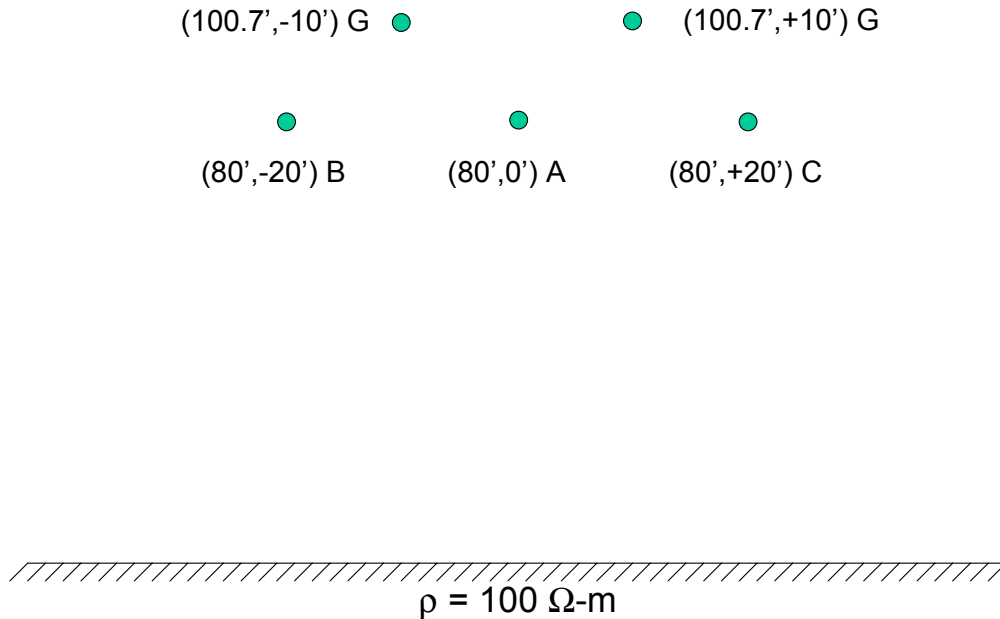
(100.7',-10') G ●   ● (100.7',+10') G

●   ●   ●

(80',-20') B   (80',0') A   (80',+20') C

///
$\rho = 100\ \Omega\text{-m}$

Fig. 2 Cross section of the transmission line used to simulate the Mead-Perkins line

The towers were assumed to be spaced 0.2 miles apart and to have a (measured) grounding resistance of 8.1 Ω. The transmission line was assumed to be 21.6 miles in length. The exact length is unimportant since the distant end is much farther from the fault than the substation. As a result, even if it was energized, the distant end bus will contribute little to the fault current. The fault (phase A to ground) was staged one mile from the substation at tower # 1/5 by first open circuiting both ends of the line, grounding one phase and then energizing the circuit from the Mead Substation.

2.3 Model Used to Validate the Test
A full three-phase circuit model of the bolted fault test is shown in Fig. 3 below. Note that while the resistances of the conductors and capacitances between the conductors are not shown explicitly in the figure, they are included in the model. Fig. 3 can be used to identify the parameters that are needed to calculate the fault currents and that are described as follows. The three phase Thevenin equivalent source (V_A, V_B, V_C and Z_{TH}) is shown to the left of the diagram. The magnitudes of the phase to ground voltages, V_A, V_B, and V_C, of the 500 kV line are 289 kV and the phases are 0, -120 and 120 degrees respectively. The values of the Thevenin equivalent impedances are dependent upon the system that drives the line and will be given after the sequence network is introduced. The line impedances (resistance per unit length and self and mutual capacitance and inductance per unit length) are determined from the cross sectional locations of the

4

conductors shown in Fig. 2, the diameters and resistances per unit length of the conductors given above, as well as appropriate frequency dependence for the resistance of the conductors. The impedances include L_{line} (the equivalent line inductance) and L_{GW} (the ground wire inductance) are shown in Fig. 3.
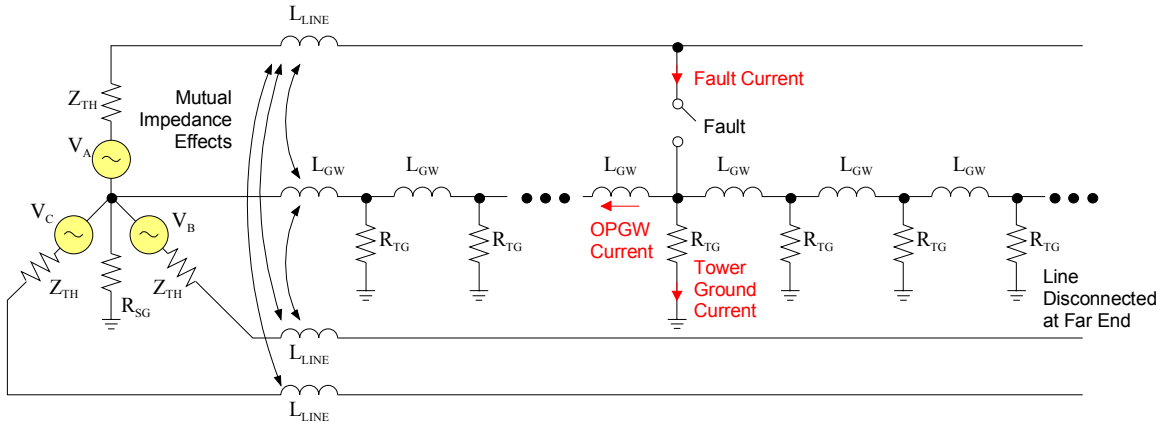

Fig. 3. Three phase Equivalent Circuit for a single phase to ground fault

The substation and faulted tower grounds are represented by physical models of the actual ground configurations. The substation ground that is illustrated in Fig. 4 is a rectangular mat with an overall size of 120' by 150' constructed of twenty 30' by 30' meshes. The conductors are 4/0 Copper and buried 1.5' in the ground. The ground resistance (R_{SG} in Fig. 3) for this mat is 1.73 Ohms. The tower ground is illustrated in Fig. 5. Beneath each tower footing is a 4' by 4' mesh made of 5/8" steel rod and buried 6 feet in the ground. Also connected to each mesh are three 5/8" diameter copper clad rods that extend from the surface to 9.9 feet below the surface. The conductors that appear to form the remainder of the mesh in the figure actually represent the tower superstructure and are not used in the grounding calculations. The resistance for this ground system is calculated to be 8.23 Ohms (R_{TG} at the faulted tower in Fig. 3). This value is quite close to the measured 8.1 Ohm tower footing resistance reported by WAPA [1].

It is assumed here that the shield wires are either grounded (through $R_{TG} = 8.1$ Ohms) or left open circuited. The latter is chosen if the shield wires are insulated from ground and the standoff insulator is not flashed over. For the Mead – Perkins line, insulated shield wires were used. It is assumed that the shield wire insulators on the three towers closest to the faulted tower (on both sides) have flashed over with zero impedance. The result is that R_{TG} in Fig. 3 is set to 8.1 Ω at three towers on either side of the fault and to infinity everywhere else.
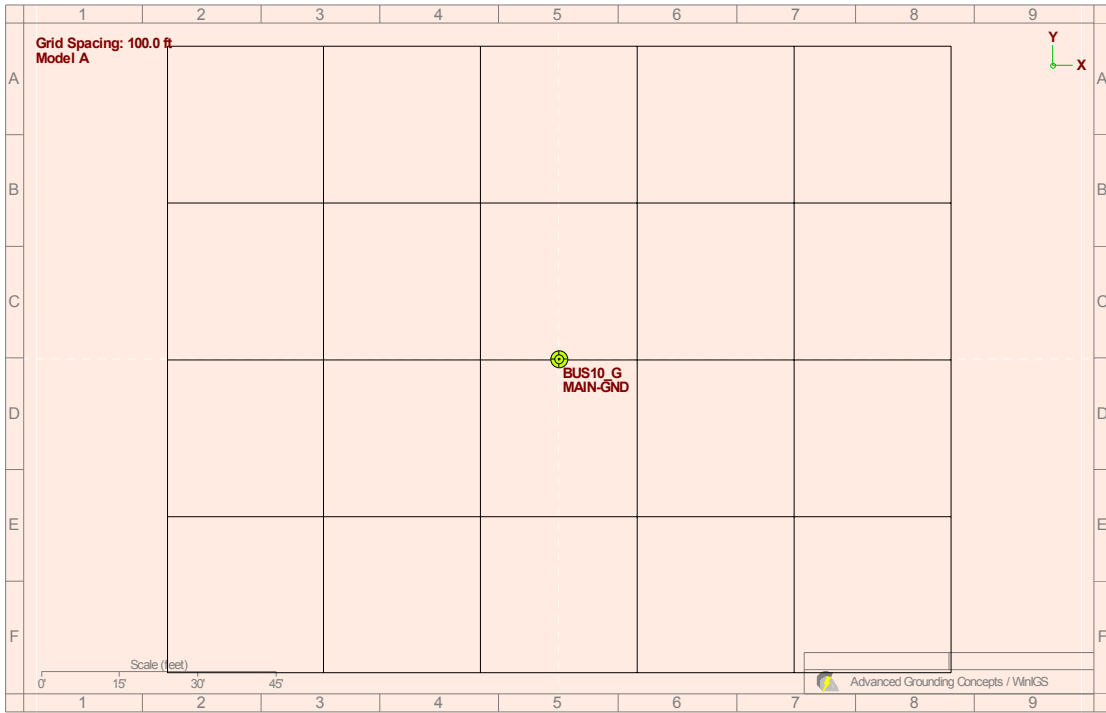
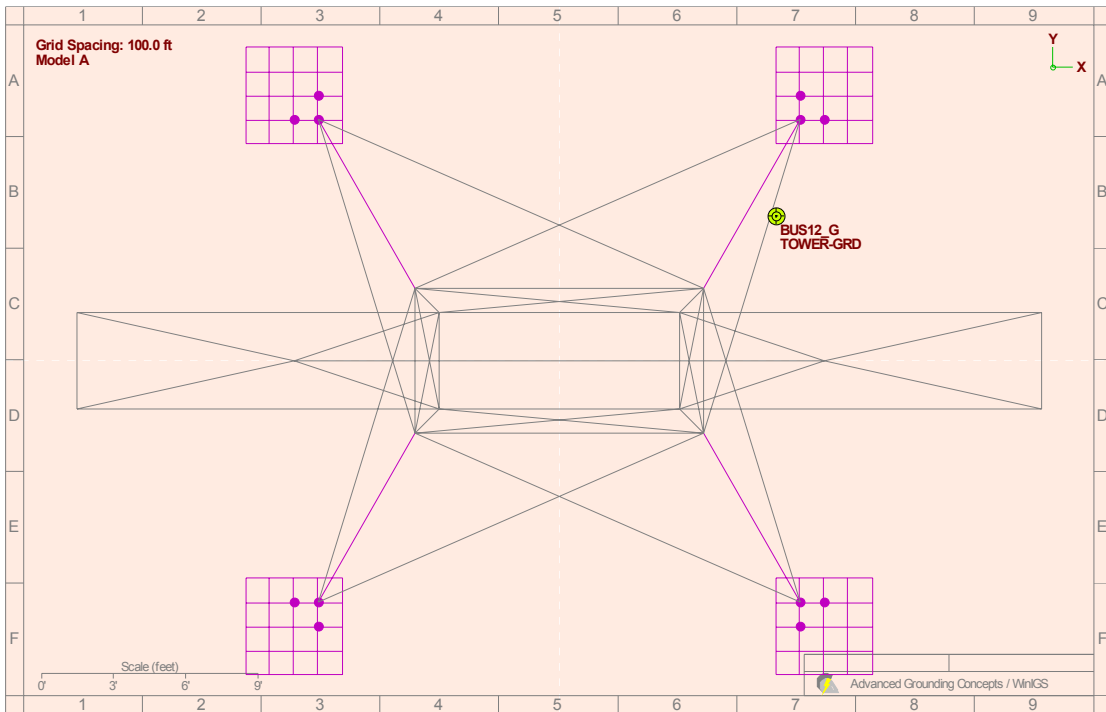**Fig. 4 Substation Ground Mat for the Mead-Perkins Bolted Fault Test**

Fig. 5. Grounding arrangement for the faulted tower

Also designated on Fig. 3 are the specific currents measured by Western Area Power Administration personnel during the test. These were the "fault" current, and for the tower at which the "fault" occurs, the total wire current on the shield wire (both directions) to other tower grounds and the total tower current to ground.

Since sequence networks are usually used to solve for fault currents, the equivalent sequence network is shown in Fig. 6. Again, the specific currents measured by Western Area Power Administration personnel during the test are indicated in Fig. 7[1].

The positive, negative and zero sequence line impedances can be calculated from the self and mutual line impedances noted in Fig. 3. The Thevenin sequence impedances for system behind the Mead 525-kV bus were calculated (at the time of the staged fault test) to be

$$Z_{TH} \text{ (positive sequence)} = Z^+_{TH} = 0.75 + j\, 18.42 \text{ Ohms}$$
$$Z_{TH} \text{ (negative sequence)} = Z^-_{TH} = 0.75 + j\, 18.42 \text{ Ohms}$$
$$Z_{TH} \text{ (zero sequence)} = Z^0_{TH} = 7.55 + j\, 41.58 \text{ Ohms}$$

Given the information above, it is, in principle, possible to calculate the fault, ground and shield currents shown in Figs. 3 and 6 that occurred during the bolted fault test. These can then be compared to the measured values.
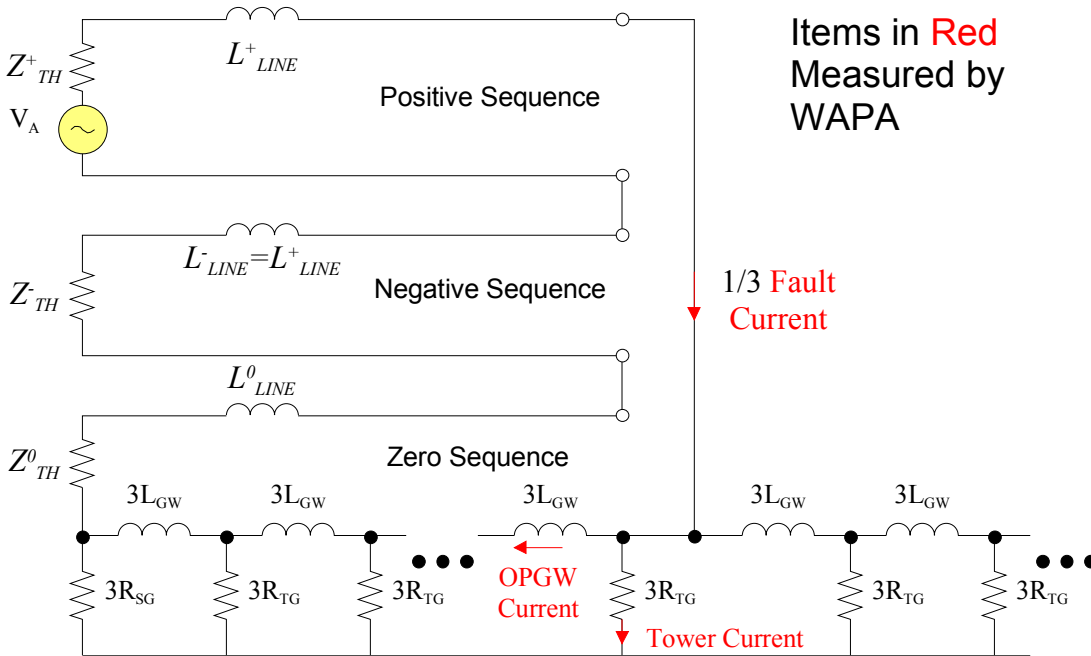
Fig. 6. Sequence network connection for line to ground fault

In order to evaluate the safety of working on the ground during fault conditions, WAPA personnel also made several measurements of touch and transferred touch potentials

---

[1] In the sequence network, the current predicted is 1/3 of the actual fault current.

during the fault. The physical model that shows where these measurements were taken is shown in Fig. 7. More specifically, the potential measurements were made at 3.3 feet (1 meter), 9.9 feet (3 meters) and 33 feet (10 meters) away from the center of one of the tower footings and were measured with respect to the tower voltage (i.e. the ground potential rise). Note that the input for this calculation is the tower ground current injected into the earth that can be calculated using the circuit of Fig. 6. The prediction of the touch and transferred touch potentials is done by injecting into the tower (and hence also the earth) this tower fault current and solving for the potential distribution in the earth using LaPlace's equation.
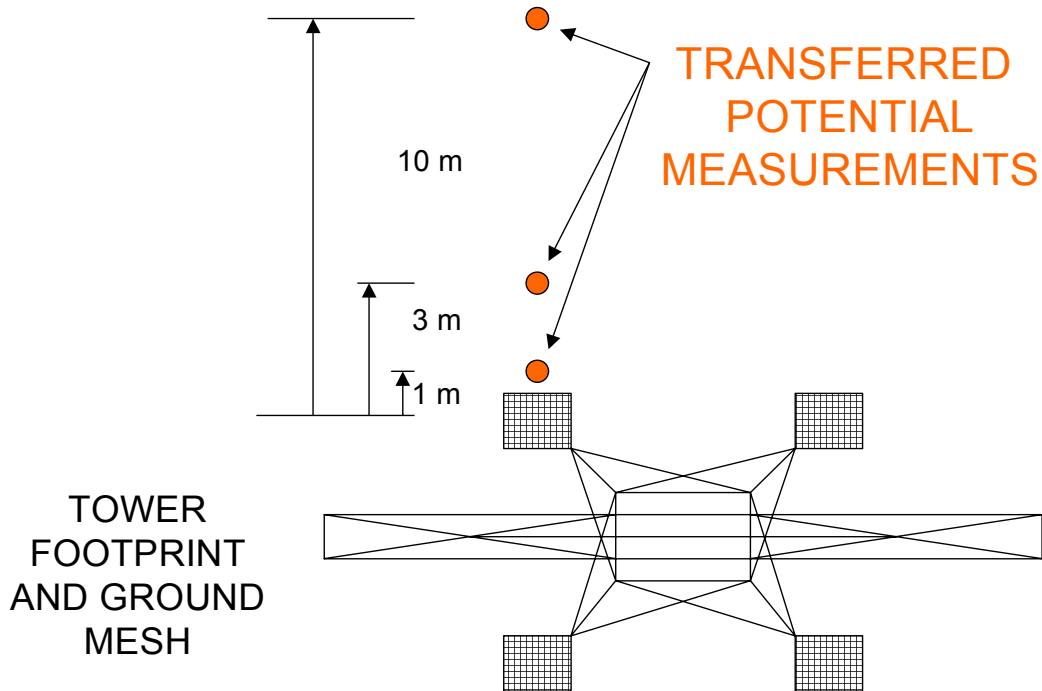

Fig. 7. Geometry for the transferred potential measurements

It is important to note that in developing the model, a number of assumptions have been made. They are:

1. the tower grounding resistances are assumed to be linear[2];
2. the tower grounds are assumed to be identical;
3. the earth conductivity is assumed to be linear, homogeneous and isotropic;
4. the tower grounds are equally spaced; and
5. quasi-steady state calculations are used.

As mentioned previously, these assumptions are all questionable. This is the reason for the validation.

---

[2] Note: in the actual model used, the resistances are modeled by arrays of wires in contact with the earth designed to mimic the actual measured ground resistance.

2.4 Comparison of Calculated and Measured Results

Although the steps described above were used in the calculation, the actual calculations were performed using WinIGS Software [2,3]. The results are shown in Table I.

According to Table I, the largest difference between simulation and measurement was approximately 19% while the average difference was approximately 9%. Given expected uncertainties in the model parameters, this result appears reasonable and appears to validate the modeling assumptions made during this work. While the problems that will be solved later are different and one cannot ensure the same accuracy, the confidence level that one has in the modeling effort is enhanced by these results.

Table I Comparison between calculated and measured results with voltages measured with respect to the tower voltage.

	Measured	Calculated	Percentage Difference
Fault Current	11,140 A	10,347 A	-7.1%
Total Tower to Ground Current	1112 A	1253 A	+12.7%
Total Ground Wire Current	8580 A	8908 A	+3.8%
Touch Potential (3.3 feet)	2830 V	3363 V	+18.8%
Transferred Touch Potential (9.9 feet)	6510 V	5863 V	-9.9%
Transferred Touch Potential (33 feet)	7830 V	7963 V	+1.7%

3

SIMULATION OF THE OPGW SAFETY PROBLEM

3.1 Introduction

In this section, a model will be developed that is relevant to the question of whether it is possible to safely maintain OPGW optical fiber systems (e.g. splicing) while a transmission line is energized. Specifically, calculations will be made of the current induced in a simulated human on the ground who is touching OPGW while the line is energized and there is a phase to ground fault.

Prior to describing the model, however, it is important to discuss certain assumptions that limit the scope of the work. These assumptions are discussed in the next few paragraphs.

3.2 Modeling Assumptions

Lightning flashes that do not cause "insulator failure" (i.e. those that do not cause a phase to ground flashover) will not be specifically considered in this modeling. Their impact on safety is of less concern than system faults due in part to their shorter duration and in part due to the fact that the human body is more tolerant of the higher frequency content contained in lightning current impulses. Further, the effect of lightning currents was beyond the scope of the work proposed for this project.

Calculations were made using the "quasi steady-state" assumption [4]. In other words, steady state theory will be used to calculate the system voltages and currents prior to and after the fault. In making this assumption, the initial transient response of the system due to the inductive reactance of transmission lines will be ignored. These transients are known to exist at the beginning of a fault but their duration is short. Transient current amplitudes vary with the specific time during the cycle at which the fault occurs and are limited by the ratio of system reactance to resistance (i.e. X/R) for the case under consideration. Rather than try to specifically model these transients, a safety factor (relative to the "quasi steady-state" calculations) consistent with that discussed in IEEE Standard 80 will be used [5].

It will be assumed that the equivalent circuit for the system that drives the transmission line under study is known and is linear. Given the assumption of linearity, the system can be characterized by a range of typical sequence impedances that represents a reasonable range of substations. Using this range, results applicable to a reasonable set of typical scenarios will be developed. The transformers feeding the transmission lines will be standard D-Y connected with the secondary connected to the substation ground. It will

also be assumed that the earth (and hence all tower resistances and earth resistivities) is linear for the range of fault currents expected.
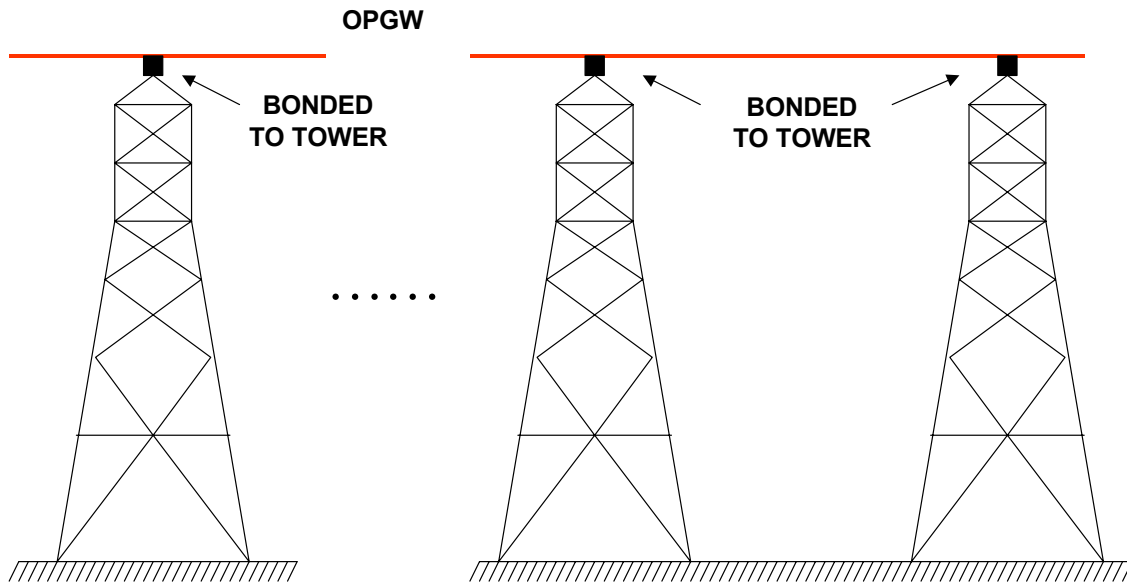

Fig. 8. OPGW installation for which it is bonded to the tower at each tower

Utility policies on grounding of OPGW differ. Some ground it at each tower while others (in order to minimize ground wire losses and to mitigate concerns about touch potentials) will insulate it at every tower that does not have a splice box [6]. Here, both grounded and insulated OPGW cases will be studied. If the OPGW is grounded at every tower, the analysis is relatively easy to set up as illustrated in Fig. 8. It is simply assumed that the ground wire is bonded to the tower at each tower.

If, however, the OPGW is insulated from the towers, there are a number of questions to be addressed. Consider the OPGW system shown in Fig. 9.

If the insulated configuration shown in Fig. 9 is used, it will be assumed that an optical isolator is used in order to prevent the flow of inductively-induced 60 Hertz currents. To do this it will be assumed that the tower standoff and dead-end insulators will flashover at lower voltages than the optical isolator. Here it will be assumed that during the fault the voltages across the standoff and optical isolator insulators are large enough to flashover for the first three towers away from the flashover point occurs. Other scenarios can be studied, but these results will not be reported.

It will also be assumed that the splice box and the OPGW cable (below the optical isolator) are bonded to the tower. Finally, it will be assumed that the work table or truck where the work is being carried out is at local ground potential.
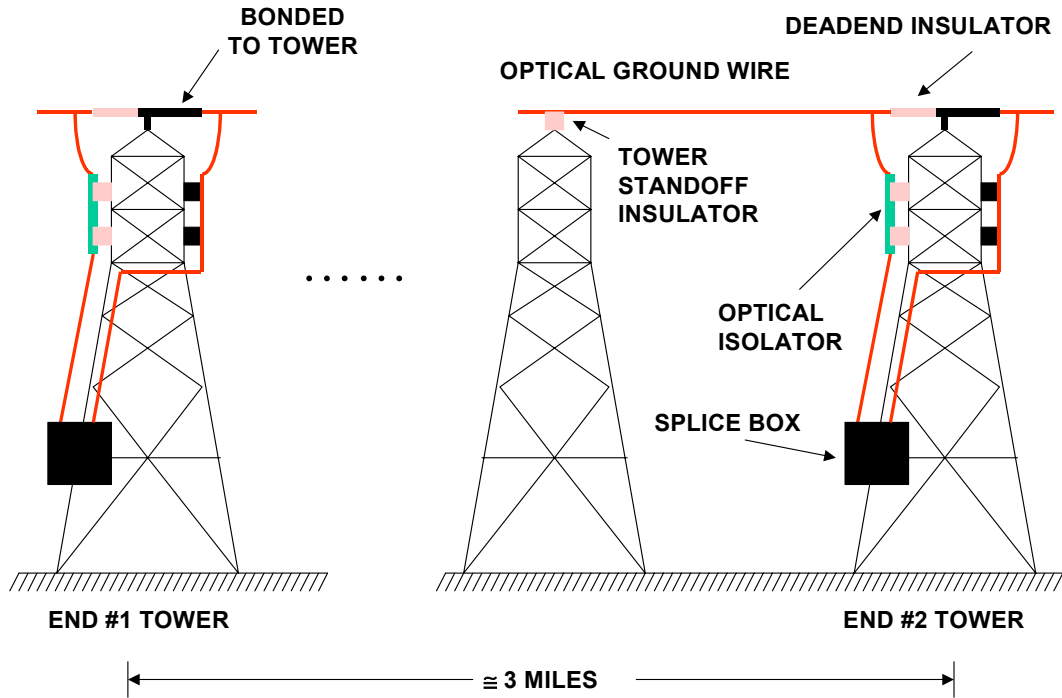
Fig. 9. Transmission Line Configuration with Insulated OPGW

3.3 Description of the Systems Under Study

The two power line geometries that were studied here will now be described. Both lines were 230 kV and used "bittern" phase conductors (diameter of 1.345" and a DC resistance of 0.0738 Ω/mile) and ground wires that were either 3/8 inch EHS or OXLIP to simulate the size of OPGW cable. The earth was modeled to be a single layer of resistivity 100 Ω-meters.

The first transmission line modeled was a double circuit 230 kV transmission line (on a single tower) with the cross section shown in Fig. 10. The letters A, B, C and G refer to specific phase conductors and ground wires respectively. The ground wires at x = -12 and x = 12 are respectively 3/8 inch EHS and OXLIP.

The distributed line parameter parameters for this system can be determined from the cross sectional diagram of Fig. 10 along with the radii given above.

The system that these transmission lines are assumed to be part of is shown schematically as a WinIGS system diagram in Fig. 11. The circuit on the left side of Fig. 10 is energized at both ends by identical 230 kV substations as shown in Fig. 11, while the circuit on the right side of Fig. 10 is floating and simulates a transmission line that is de-energized but capacitively and inductively coupled to the first circuit. It is assumed, however, that shield wires however, are connected to each other.
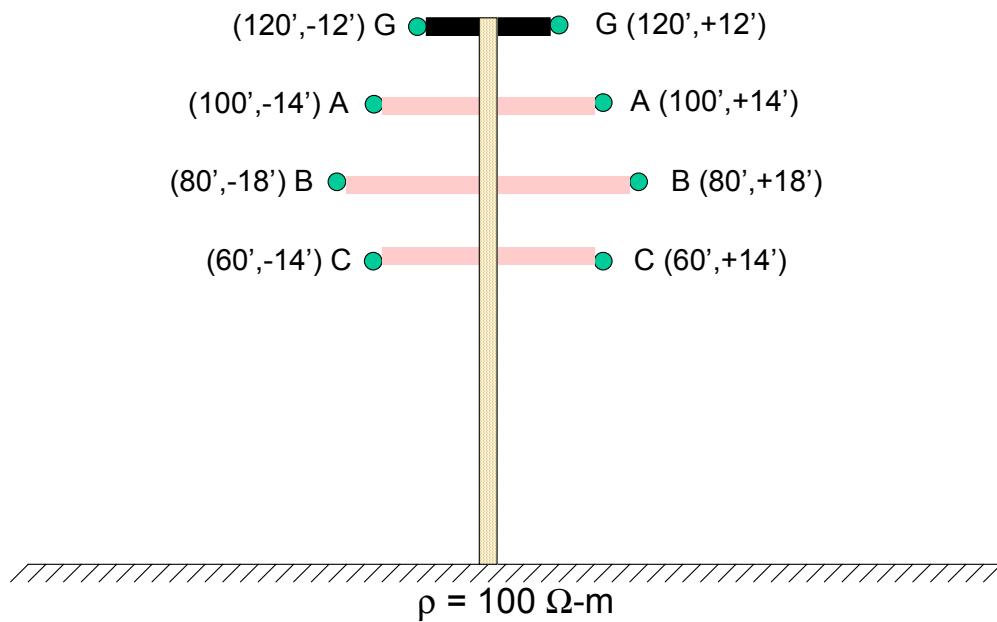
Fig. 10. Cross sectional geometry of the first simulated transmission lines

Each substation is connected to a ground mat that is illustrated in Fig. 12. The mat is buried at 1.5 feet under the surface and is constructed of #4/0 copper wire in a one layer earth model with resistivity 100 Ω-m. Each grid square is 40 x 40 feet and there are 9 x 10 grid squares. The connection between the generator neutral and the ground grid is at the center of the ground grid and that the resistance of each substation ground is 0.59 Ω.
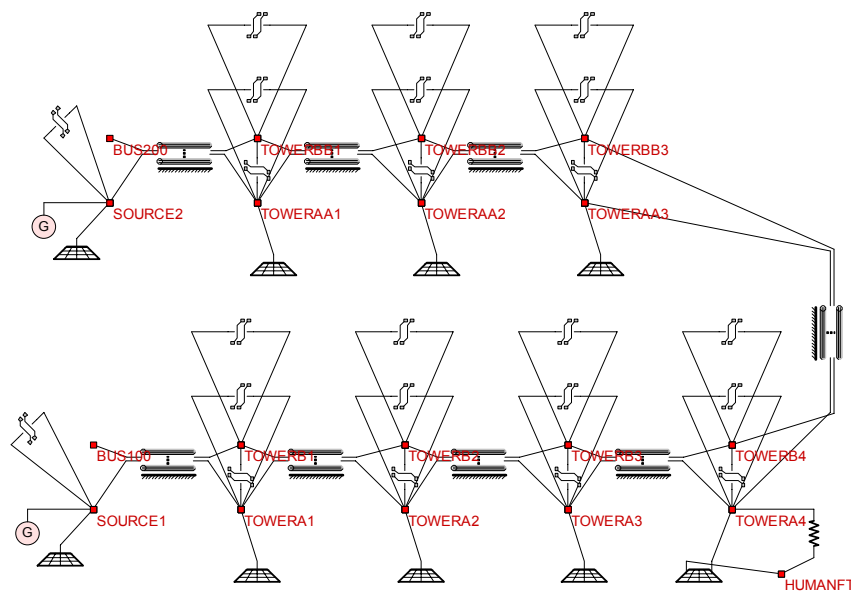

Fig. 11. Schematic of the system used to study OPGW maintenance safety
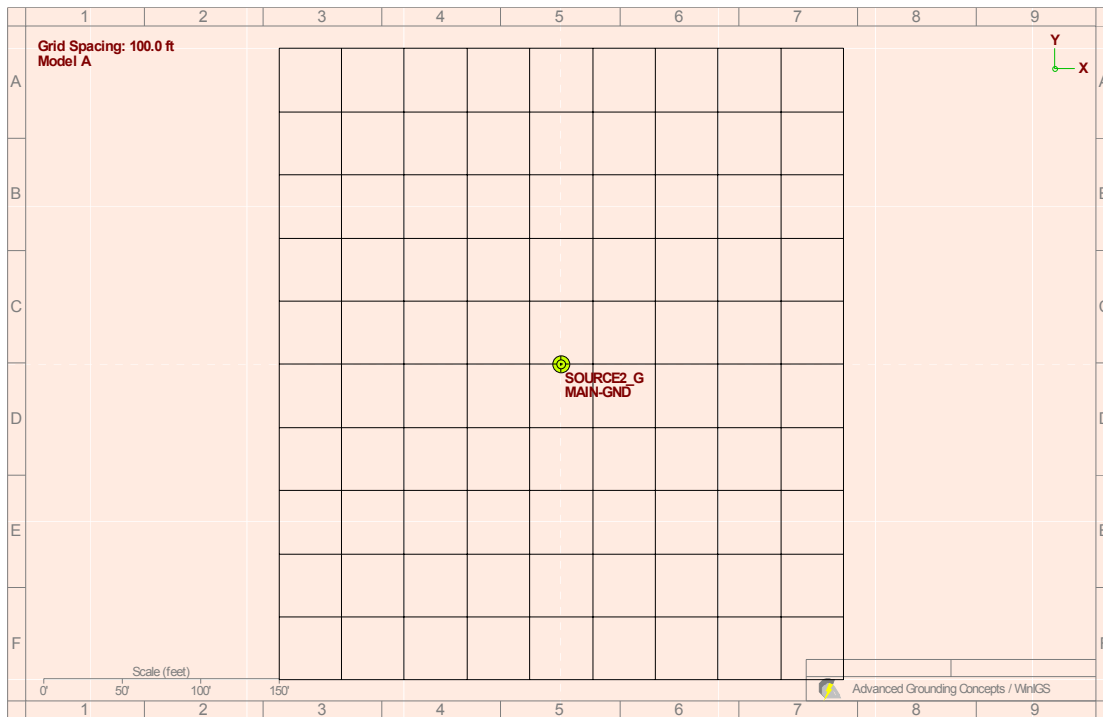
13

Fig. 12. The ground mat at each substation

Two substation models are used. The first has a short circuit current of approximately 34 kA for each phase. The Thevenin positive and negative sequence impedances are 0.0159 +j 3.8987 Ω while the Thevenin zero sequence impedance is 0.1598 +j 4.5827 Ω. The second has a short circuit current of approximately 10 kA for each phase. In this case, the Thevenin positive and negative sequence impedances are 0.0529 +j 12.9958 Ω while the Thevenin zero sequence impedance is 0.5325 +j 15.2758 Ω.

The ground grid for each of tower is assumed to be that shown in Fig. 13. The rectangular meshes under each tower foot are constructed to be 3 x 3 feet in diameter, buried 3.5 feet in the earth and made of #4/0 copper wire. Each of these meshes is supplemented with three driven ground rods as shown in the figure. Each rod is copper, 5/8" in diameter and 9 feet in length. The remainder of the grid shown in the figure represents the tower superstructure and does not affect the calculations of currents and voltages reported in this paper. The grounding resistance of each of these complete grounds is found to be approximately 9.4 Ω.

As mentioned above, both insulated and uninsulated OPGW systems were studied. When uninsulated, all towers are assumed to be grounded through a grounding electrode identical to that shown in Fig. 13. When insulated, it is assumed that the standoff insulators on each tower within three towers of the faulted tower will flashover with zero impedance. For the remainder of the towers, it is assumed that no current passes from the ground wire through the tower to ground although the ground wires do carry return current to the substation.
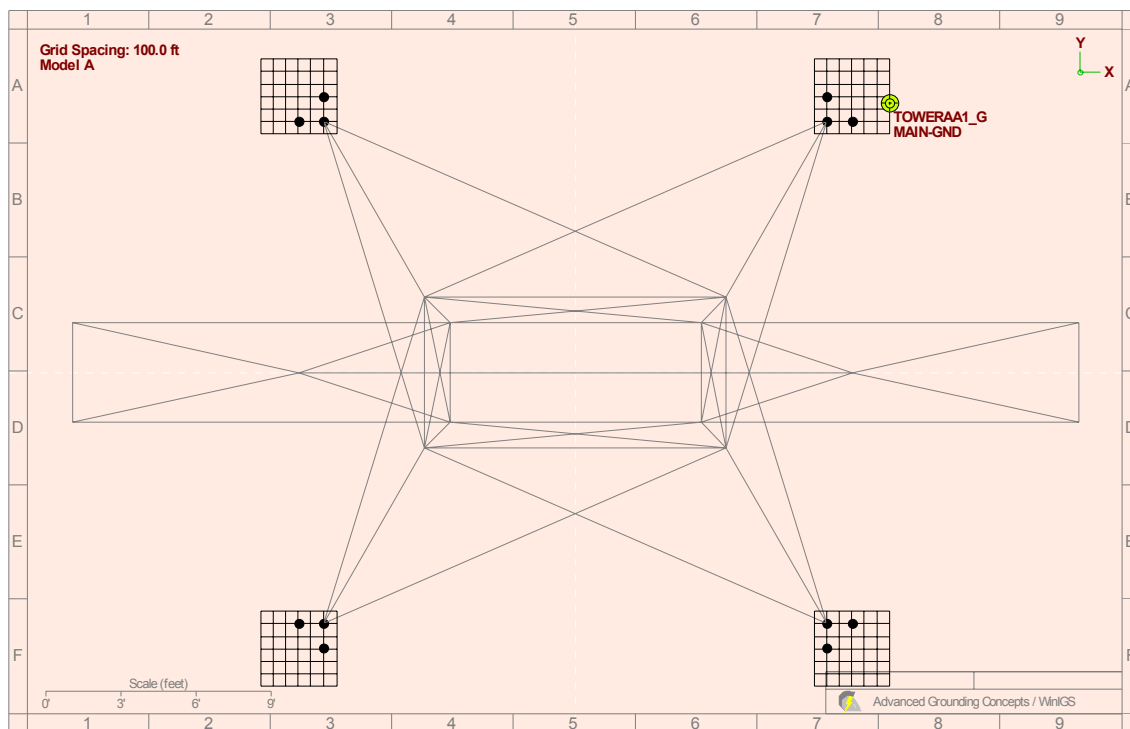
14

Fig. 13. Layout of each tower ground

It is assumed that the total length of the transmission line is 21.3 miles that the fault occurs at a distance 0.85 miles from one end of the line. Near the fault, the towers are assumed to be spaced 0.15 miles apart.

At approximately 20 feet from the tower where the fault occurs, a model for a human foot has been placed in contact with the earth. This model consists of a 1 x 0.5 foot square mesh of #12 copper buried 0.1 feet in the ground. A human in contact simultaneously with this point and the tower (via the transferred potential due to the optical ground wire) is also shown in the figure. As suggested in IEEE Standard 80, this worker is represented by a 1000 Ω resistor.   The current through this resistor is that which would be experienced by the worker during a fault. A schematic of this foot that shows its location relative to the tower is shown in Fig. 14 [5].

The second transmission line modeled was similar to the first except that the two circuits were now assumed to be located on separate towers connected to separate grounds and that the spacing between the two circuits was increased by 75 feet as shown in Fig. 15. Again, the letters A, B, C and G refer to specific phase conductors and ground wires respectively. The ground wires at x = -12 and x = 87 are 3/8 inch EHS and OXLIP respectively. As before, the distributed line parameters for this system can be determined from the cross sectional diagram of Fig. 15 along with the conductor radii given earlier.

15

Except for the differences listed in the last paragraph, the system is identical to that used for the first calculation in Fig. 11. As earlier, the circuit on the left side of Fig. 15 is energized at both ends by identical 230 kV substations as shown in Fig. 11, while the
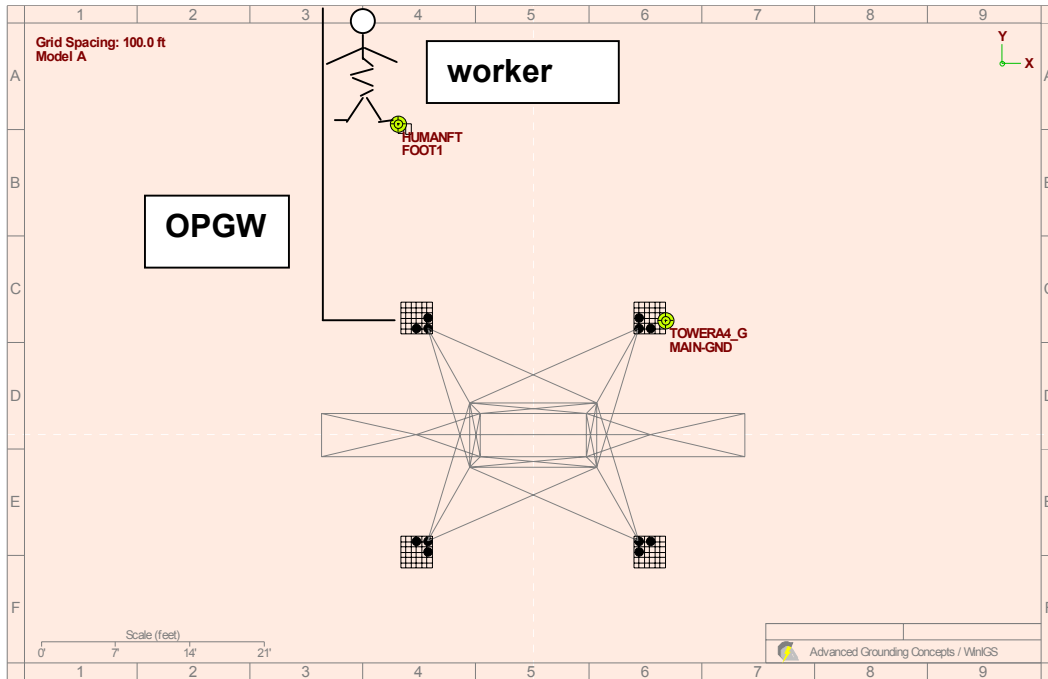

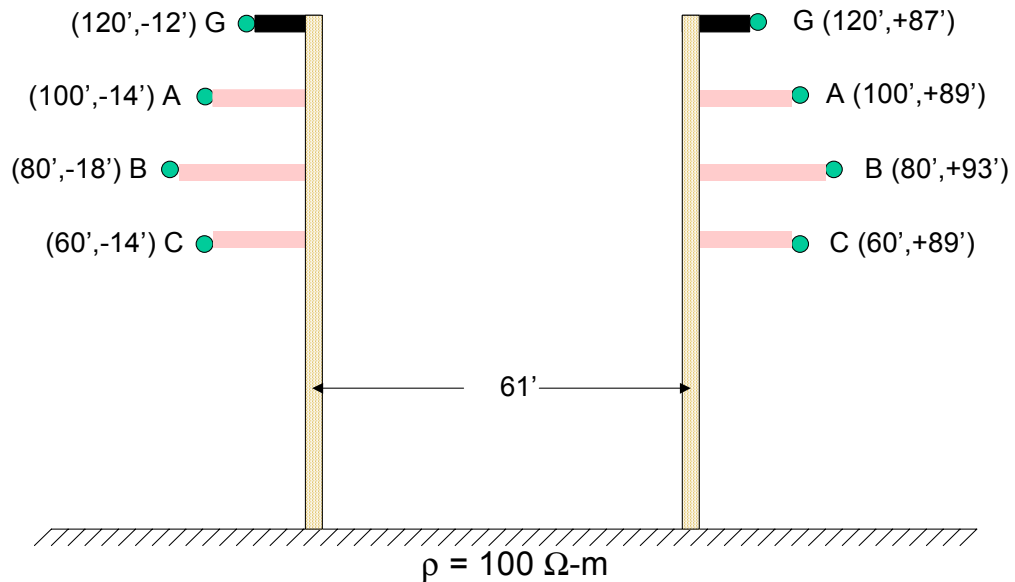**Fig. 14. Location of the human foot relative to the tower**

Fig. 15. Cross sectional geometry of the second simulated transmission lines

circuit on the right side of Fig. 15 is floating and simulates a transmission line that is de-energized but capacitively and inductively coupled to the first circuit. Note also that it is not assumed that shield wires are connected to each other. The purpose for studying this line was to allow evaluation of the safety of working on the de-energized circuit while the other is energized.
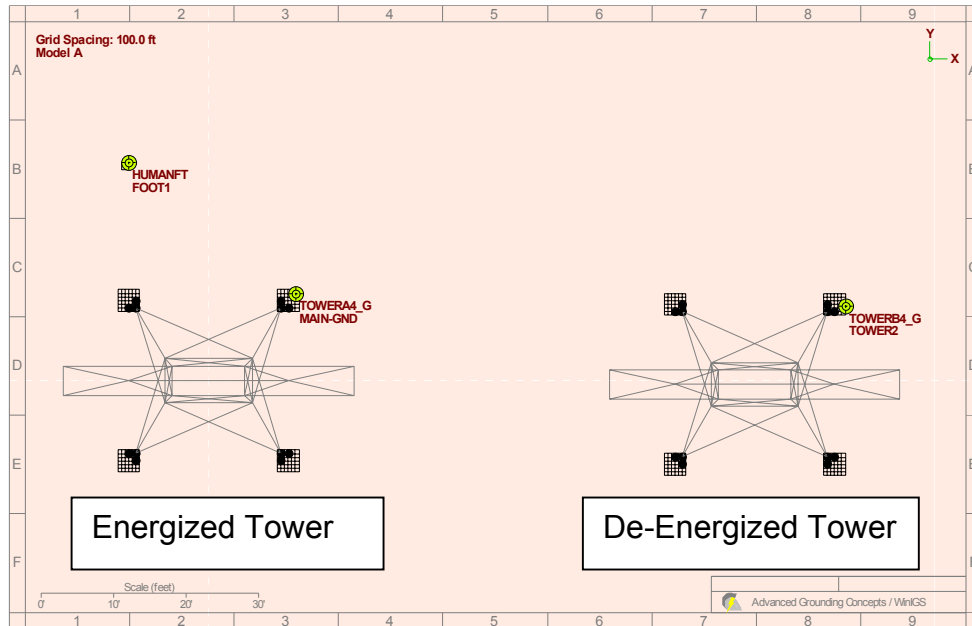

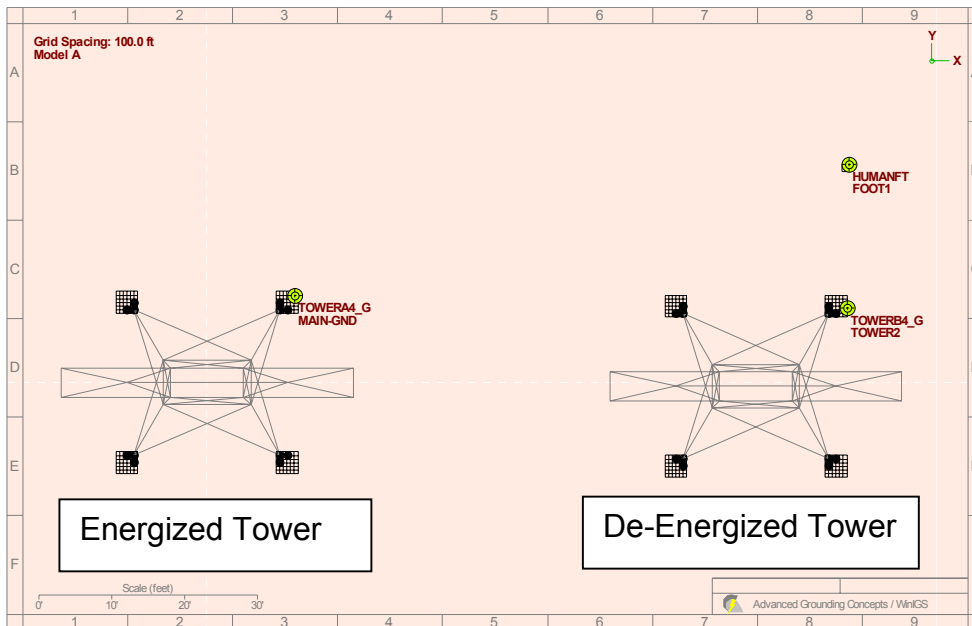**Fig. 16. Location of human foot near the energized tower**

Fig. 17. Location of human foot near the de-energized tower

Again, each substation is connected to a ground mat that was described earlier and is illustrated in Fig. 12.   In this case only the substation model with a 10 kA short circuit current was used. The Thevenin positive, negative and zero sequence impedances for this substation case were given earlier. Finally, the ground grid for each of tower is assumed to be that shown in Fig. 13. Again, details were given earlier.

Two locations for the human foot were assumed; one 20 feet from the energized tower and one 20 feet from the de-energized tower as shown in Figures 16 and 17 respectively. As before, the human in contact simultaneously with this point and the tower (via the transferred potential due to the optical ground wire) is represented by a 1000 Ω resistor.

4

RELEVANT SAFETY STANDARDS

Prior to presenting the results, it is important to discuss the standards that apply to human exposure to electrical shocks of short duration.

According to IEEE Standard 80, it has been shown that the maximum 50/60 Hertz shock current (I_B) that can be survived by 99.5% of all persons weighing 70 kg [5] is

$$I_B = \frac{157}{\sqrt{t_s}} \quad mA \tag{1}$$

where t_s is the duration of the current. If it is assumed that shock duration is limited by the clearing time of backup relays (to be consistent with standard practice for safety assessment) and that this time is 15 cycles or 0.25 sec for 60 Hertz, then the maximum tolerable current is

$$I_B = 314 \ mA. \tag{2}$$

It is well known that the fault current can be asymmetric (i.e. it has a slowly decaying dc component). The amount of offset depends upon the value of X/R for the system that drives the fault current. Given this, the allowable body current should be reduced by a "Decrement Factor" D_f. According to IEEE Standard 80, Table 10, the maximum value of this factor for systems with X/R < 40 and a fault duration of 0.25 sec, is $D_f = 1.2$. For purposes of this report then, the maximum tolerable body current will be

$$I'_B = I_B / D_f = 262 \ mA. \tag{3}$$

19

5

RESULTS

_____

For all of the simulation to be reported here, a phase A to ground fault was assumed to occur at Tower A4 shown in Fig. 11. All of the other values of current and voltage reported here are a result of that fault.

5.1 Double Circuit Transmission Line

The results for the total fault current, transferred potential (relative to the tower) at the human's location and the current introduced into the human are shown in Table II.

Table II Results for the Double Circuit Line

Substation Model	Insulated/Grounded Shield Wire	Transferred Potential (relative to tower)	Current in Human	Total Fault Current
34 kA	insulated	18.38 kV	15.18 A	29.14 kA
34 kA	grounded	7.25 kV	6.00 A	29.57 kA
10 kA	insulated	7.90 kV	6.54 A	12.34 kA
10 kA	grounded	3.03 kV	2.51 A	12.50 kA

It is clear that in all cases, the currents introduced into the human far exceed that allowed by safety standards. If work is to be done on such a line while it is energized, some mitigative action will have to be taken. An example of how this could be done will be discussed in the next section.

5.2 The Two Separated Single Circuit Transmission Lines

The results for the total fault current, transferred potential (relative to the tower) at the human's location and the current introduced into the human are shown in Table III.

Table III   Results for the Two Separated Single Circuit Lines – 10 kA Substation

Near Energized or De-Energized Tower	Insulated/Grounded Shield Wire	Transferred Potential (relative to tower)	Current in Human	Total Fault Current
energized	insulated	14.0 kV	11.56 A	12.12 kA
de-energized	insulated	0.256 kV	0.36 A	12.12 kA
energized	grounded	11.42 kV	9.44 A	12.21 kA
de-energized	grounded	0.663 kV	0.55 A	12.21 kA

6

Conclusions and Recommendations

_____

It has been found that unless special measures are taken to protect workers, they may be exposed to dangerous levels of voltage and current during a fault. This conclusion is true even if the work is being performed on a de-energized line that is parallel to an energized line on which a fault occurs.

One solution to this problem is the installation of a temporary ground mat underneath the work area as shown in Fig. 18. By bonding the OPGW and the truck or tent in which the maintenance work is being performed to this mat, the voltage and current levels to which workers are exposed during fault conditions are significantly reduced. This reduction occurs because a low resistance bypass is provided for the fault current that flows through the OPGW to the earth.
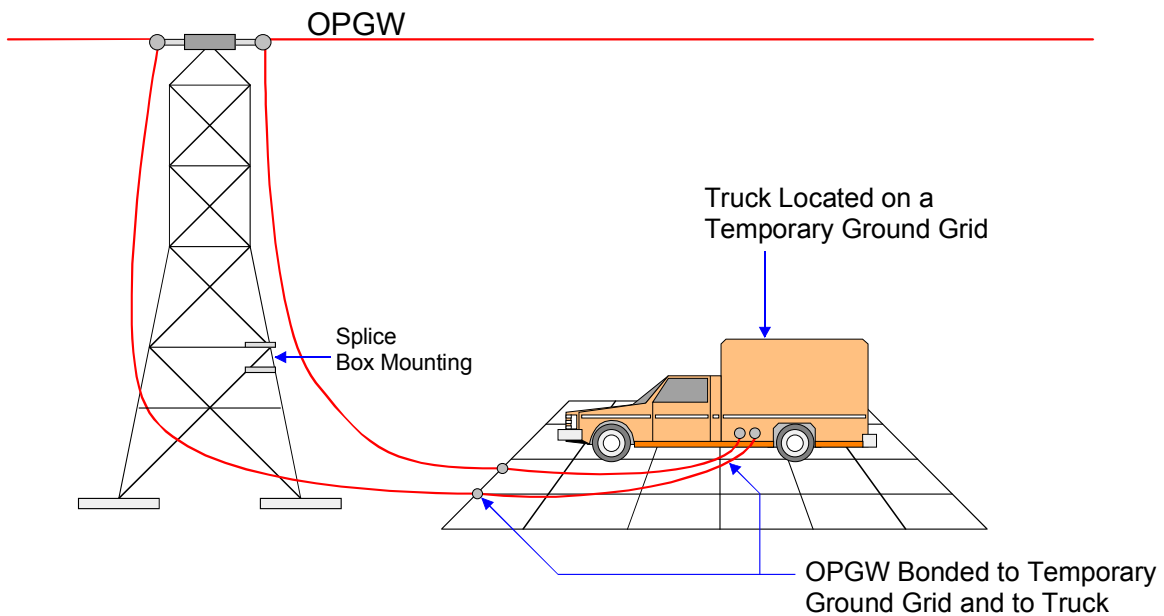

Fig. 18. The use of a temporary ground grid to perform maintenance on OPGW

7

References

_____

1. P. Atwater, J. DeHaan, and L. Romero, "Utilities Field Test Safety Grounds," *Transmission and Distribution World*, November 2000, pp 44 – 56.

2. WinIGS Software, Available from Advanced Grounding Concepts, 1886 Fisher Trail NE, Atlanta, GA 30345-3466.

3. A. P. Sakis Meliopoulos, Feng Xia, E. B. Joy, and G. J. Cokkinides, 'An Advanced Computer Model for Grounding System Analysis,' *IEEE Transactions on Power Delivery*, Vol 8, No. 1, pp 13-23, January 1993.

4. R.G. Olsen and M.C. Willis, "A Comparison of Exact and Quasi-Static Methods for Evaluating Grounding Systems at High Frequencies, *IEEE Trans. on Power Delivery,* Vol. 11, pp. 1071-1081, April 1999.

5. IEEE Standard 80, (IEEE Guide for Safety in AC Substation Grounding 2000), available from the Institute for Electrical and Electronics Engineers, New York.

6. M. W. Tuominen, "500 kV Overhead Shield Wires : Sectionalize of Ground Everywhere?" Proceedings of the 1992 American Power Conference, Chicago, IL.