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Substation Cable Layouts for EMP Coupling Analysis

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ABSTRACT

Direct coupling of early-time high-altitude electromagnetic pulse (HEMP) to substation control cables is simulated for cable layouts based on surveys of seven electrical substations in the United States. An analytic transmission line modeling code is used to estimate worst-case coupled current at the terminations of cable segments in or near the control shack. Where applicable, an induced voltage due to cable shield grounding is also estimated. Various configurations are simulated, including cables with different elevations, lengths, radii, and terminations. Plots of the coupled HEMP effects are given, and general relationships between these effects and the substations' geometric and material parameters are highlighted and discussed.

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EXECUTIVE SUMMARY

Background

High-altitude electromagnetic pulse (HEMP) poses a significant threat to electrical infrastructure. Induced currents on power lines as well as on control cables in electrical substations exposed to the potentially extreme early-time radiated environment (E1) may disrupt or even damage connected equipment and cause widespread loss of electrical power over a large geographical area. The nature of the problem often requires that experimental analyses of power system resilience to these effects be supplemented with numerical simulations. This report gives numerical analyses of simplified geometries of control cable layouts based on several substations throughout the continental United States. The purpose is to estimate worst-case effects of direct HEMP coupling to various layouts of substation cables, and also to estimate the voltage levels induced on control wires due to currents flowing on grounded cable shields.

Analysis

The principal tool used for numerical analysis was Sandia's Analytic Transmission Line Over Ground software (ATLOG), which computes HEMP-E1 coupling to a single insulated straight transmission line of finite or infinite length. Cable segments with geometries based on those in the substations surveyed are modeled in order to estimate the worst-case coupled currents, as well as induced voltages in the case of shielded cables, that may be expected at the cable's termination in or near the substation control shack.

Limitations

Due to the limited capabilities of the ATLOG software, the geometry of the cable layouts studied required significant simplification. Since the actual layouts in question were made up of long straight wires at right angles to each other, breaking down the problem into simple parts for simulation in ATLOG was possible while still retaining certain significant geometric parameters. The straight-line cable segments, however, had to be simulated separately, without connection to one another.

Additional simplifications included the modeling of terminating line impedances as open and short circuits. In particular, the termination of an unshielded cable in the control house is modeled as a direct connection to ground for current calculations in order to predict the worst-case current through a low-impedance device. A worst-case open-circuit voltage is also estimated due to coupling from shield-to-ground connections where such connections are present. More specific modeling of the terminating devices' impedance characteristics may be expected to yield a more accurate result, but this is beyond the scope of this paper.

Note also that the effects of the buried substation grounding grid are not accounted for.

Conclusion

Several general conclusions are drawn from the simulations performed in this paper. First, the computed voltage induced on cable conductors by currents on shield ground connections (also called "pigtails") can be significant (up to 16 kV) depending on the pigtail configuration. Second, the voltages and currents induced on control cables by the HEMP environment were found not to vary dramatically based on the geometric configuration of the line in the substation control yard. Cables buried 3 ft beneath the soil showed a peak current reduction of around 30 % compared to cables which, in reality lying in a shallow covered trough, were modeled as lying flat on top of the ground. Moreover, the peak current induced by coupling to the longest and shortest cable runs within a given substation did not differ noticeably in the plots (except for very short lines where reflections interfered with the peak), though the longer line did show a longer decay of the induced signal.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ATLOG	Analytic Transmission Line Over Ground
EMP	Electromagnetic Pulse
E1	Early-time HEMP
HEMP	High-altitude Electromagnetic Pulse
PVC	Polyvinyl Chloride
PT	Potential Transformer
VT	Voltage Transformer
CT	Current Transformer
CVT,CCVT	Capacitor Voltage Transformer
EIGER	Electromagnetic Interactions GenERalized
ε_r	Relative Permittivity
μ_r	Relative Permeability

1. INTRODUCTION

High-altitude electromagnetic pulse (HEMP) accompanying the detonation of nuclear weapons at high altitude has the potential to interfere with or even damage electrical devices. A particular concern is the effect of the early-time pulse, called E1, on electrical distribution equipment. This includes coupling of HEMP fields not only to elevated power lines but also to electrical substations. In these facilities, measurement and switching equipment is contained in a small building, referred to here as a "control shack" or "control house". Cables connected to this equipment (referred to as "instrument cables" or "control cables" in this report) are routed out into the surrounding control yard (also called "switchyard"), generally in a buried conduit or in a covered trench, where they connect to the measurement instruments and circuit breakers used to meter or control the power delivered on the various lines leaving the substation. During a HEMP event, currents and voltages induced on the control cables may cause malfunctioning or even failure of measurement and switching equipment. Note that this direct coupling to the cables is not the only way that HEMP can affect the equipment; the induced currents on long elevated power lines can also couple to the equipment and cables, but these effects are not addressed in this report.

The threat of HEMP is increasingly being taken into account in the design of modern electrical distribution networks and equipment [5, 6, 12]. Many substations employ shielded control cables where the inner bundle of instrument wires is surrounded by a conductive shield to absorb incoming radiation (as discussed in Section 2.5, shields vary in type and efficacy). While this can at least partially mitigate the effects of HEMP coupling directly to the wires, the shield is typically grounded at one or both ends; when the induced currents on the shield travel on this ground connection they create fields that can induce significant voltages on the nearby instrument wires.

Numerous variables can affect the coupled voltages and currents induced on control cables; the conductivity of the ground influences the reflection of incident waves as well as the decay of currents traveling down a horizontal cable. The losses due to finite conductivity of cable wires as well as the wire radii will also influence this decay. These parameters, in addition to the situation of the wire relative to the ground (e.g. buried or elevated) will affect the transmission line parameters of the cable/ground system, which in turn affects the propagation speed and decay of the currents induced by an incident HEMP wave. Moreover, the terminating conditions of the control cable (e.g. a low-impedance connection to ground or an open circuit) will also determine how the induced signal is reflected at each end of the cable as well as the current that actually flows to ground at a given termination. The presence of multiple conductors in a cable can also affect the currents induced on any particular wire in the cable.

Because experimental subjection of large structures to realistic HEMP environments is generally not practical, engineers turn to numerical models in order to predict HEMP effects. Examples of such modeling efforts are discussed in e.g. [12, 2, 10].

In this report are modeled simplified cable layouts for electrical substations in order to obtain an upper-bound estimate on the currents and voltages induced by HEMP. The geometry for these models is based on the findings in [8], where further details regarding the substations themselves may be found. Coupling was simulated using a transmission line model in the software ATLOG [3, 11, 2] to calculate coupled currents induced at the control shack termination of instrument cables by a IEC-61000-2-9 waveform [4, 3] incident on the control cables in the substation switchyard.

As detailed in Section 2.3, the cable layout is modeled in three basic parts:

- the longest horizontal straight-line cable run between the control shack and an instrument in the switchyard (see Fig. 1.0.1)
- the shortest horizontal straight-line cable run between the control shack and an instrument in the switchyard
- the longest horizontal straight-line cable run (whether buried or elevated) between an instrument in the yard and the trench or buried conduit (see Fig. 1.0.2).

Figure 1.0.1. Trench for substation Layout 7.

Due to modeling software limitations the vertical cable segment that often exists between the buried or entrenched cable and an elevated cable is not considered in the calculations performed here. It should be noted, however, that in the case of grazing incidence significant currents might be induced on such segments. While an analytic estimation of the induced currents in Appendix B suggests that this effect could be significant, further work is needed to quantify it precisely. Note also that as described in [8], the substations surveyed here each employ a grounding grid beneath the substation with horizontal wires buried approximately 0.5 m or more below the ground, to which the control house and instruments are grounded. The effects of this grid are also not accounted for here due to modeling limitations, but it should be realized that the presence of this grid may significantly influence the effect of HEMP on the substation, and further work will be required to assess this influence. Further modeling simplifications are detailed in Section 2.3.

Figure 1.0.2. Instrument-to-trench elevated cables for substation Layout 2.

The main parameters that were varied in the calculations among the different substation layouts are the trench/conduit lengths and depths, the lengths and heights of the cables running between the trench and the instruments, the presence or absence of a cable shield, the grounding of the shield at either end (“Open" being ungrounded, “Short" being grounded), and the configuration, if applicable, of the shield ground (often called a “pigtail”) relative to the cable signal wires in the control shack.

The results of the analyses presented here are intended as a reference for utility engineers. First, the particular current and voltage levels for the various substation lines simulated may be used as a guide in estimating worst-case HEMP effects for similar layouts encountered in real-world substations. Second, general trends and relationships are drawn from the various simulations performed and discussed in Section 4.

With regard to the third point, several conclusions are noted in this report.

- Cable length does not significantly affect the amplitude of the induced current at a termination due to the propagation delay (see further discussion in Section 4).

- While some cables were buried ≈ 0.5 m beneath the ground, this only reduced simulated currents by about 30 % when compared with cables modeled as lying directly on top of the ground. This is likely due to the large skin depth of the ground at the frequencies of interest here.

- The estimated induced voltage on cable conductors due to currents on cable shields grounded nearby is significant in the worst case, reaching as high as 16 kV.

This report is organized as follows. Section 2 describes the numerical methods used in the analysis. Section 3 provides a basic description of each cable layout modeled, a reference to the corresponding substation in [8], diagrams explicitly showing the simplified geometries used in the models, and plots showing the computed current at the control-shack termination of the cable (and, where applicable, the voltage induced on the control wires by shield-ground connections). Section 4 discusses several general observations that may be drawn from the results in Section 3. Concluding remarks are made in Section 5, Appendix A contains a study of shielding effectiveness for a sparse stranded cable shield similar to that encountered in some of the substations under consideration, and Appendix B briefly describes an analytical approximation of HEMP-induced currents on a vertical conductor attached to an elevated line.

2. METHODS

This section describes the modeling approach used as well as certain assumptions and simplifications made for numerical modeling purposes.

2.1. Modeling Software Used

Induced currents on substation cables are computed using Sandia's Analytic Transmission Line Over Ground (ATLOG) software. This is a frequency-domain code that computes the current induced on a cylindrical wire parallel to an imperfectly conducting ground. The wire may be above or below the surface (but not partially buried) and may be covered with an insulating material of constant thickness with a specified relative permittivity (also called the "dielectric constant", symbol ε_r). Further details regarding ATLOG may be found in [3, 11, 2].

2.2. Worst-Case Approximations

In order to estimate an upper bound on the HEMP coupled voltages and currents, several worst-case approximations are made in all simulations. First, the elevation incidence angle of the HEMP wave is set to 90°, that is, normal incidence to the ground. The elevation angle θ_0 is defined in Fig. 2.2.1. Figure 2.2.1 also shows the azimuthal angle Φ ($\Phi = 0°$ **in all simulations performed here**) as well as the polarization of the incident field (this report considers only TM polarization; that is, the electric field $\mathbf{E}$ is parallel to the cable for $\Phi = 0°, \theta_0 = 90°$).

To illustrate that normal incidence ($\theta_0 = 90°$) gives maximum coupling for the horizontal cables examined here, Fig. 2.2.2 shows the coupled current at the termination of a 141.5 m long conductor with radius 1 cm covered by a 2 mm thick polyvinyl chloride (PVC) coating ($\varepsilon_r = 3.18$) over a conductive ground ($\varepsilon_r = 20$, $\sigma = 0.01\,\frac{\text{S}}{\text{m}}$) for several different heights and elevation angles of incidence θ_0. The cable is shorted to ground at both ends in this example. As may be seen in Fig. 2.2.2, the maximum induced current occurs for $\theta_0 = 90°$, or normal incidence regardless of elevation. It is also seen that a greater burial depth does give a small but noticeable reduction in peak current.

In Fig. 2.2.3 a similar study to determine worst-case incidence is performed for a short cable elevated 1.8 m off the ground, based on the heights observed in Section 3. The conditions are the same as in the previous except that the conductor has a length of 5 m, a radius of 0.5 cm, and it is covered in 3 mm of PVC, and the cable is grounded only at the end where the current is measured (the other end is open). As in the case of the long line discussed previously, maximum coupling is found at normal incidence, or $\theta_0 = 90°$.

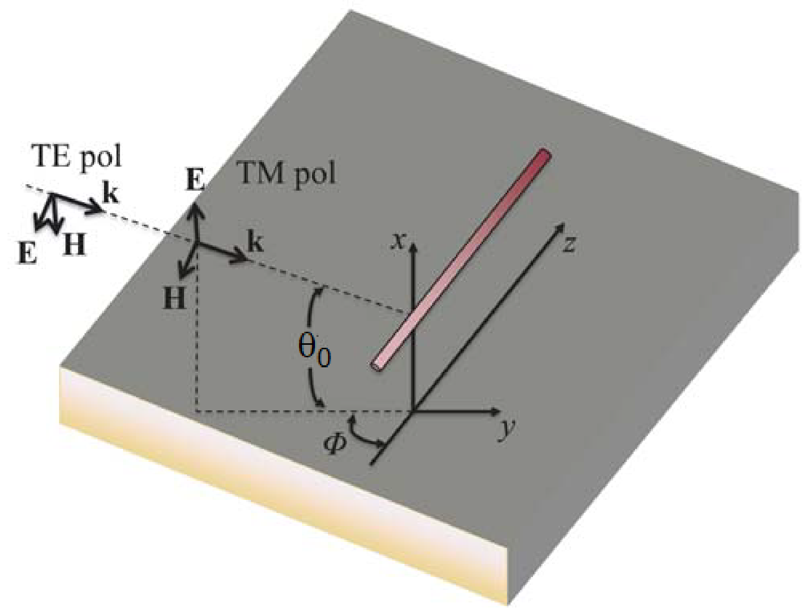


Figure 2.2.1. Orientation of cable relative to incident electric field E, magnetic field H, and direction of propagation k. Elevation angle θ_0 is indicated. The azimuthal angle Φ is also shown, but note that $\Phi = 0^\circ$ in all calculations in this report. The diagram shows both TE and TM polarizations. This report examines only TM polarization (that is, for $\Phi = 0^\circ$ and $\theta_0 = 90^\circ$ the electric field E is parallel to the cable). Image adapted from [3].

Note once again that the coupling to the vertical cable segments, for which maximum coupling will not take place at normal incidence, is not considered here.

In substations with cable shields grounded in the control shack the configuration of the shield ground (or "pigtail", see Section 2.5 for more detailed discussion) is estimated from photographs (such as Fig. 2.2.4). Since these configurations involve many wires and they are routed somewhat randomly, the estimate for the wire-shield pair configured for maximum voltage induction is used. The worst case assumption here is a parallel wire-shield pair with maximum separation (see (2.2) in Section 2.5) with the influence of other intervening wires ignored.

2.3. Simplifications

Other approximations were made due to limitations of the modeling software. One significant limitation is ATLOG's inability to simulate simultaneous coupling to a cable consisting of multiple segments with different orientations and elevations.

The physical routing of the substation cables outside the control shack consists of three main portions. One cable segment runs horizontally from the control shack into the substation switchyard. In all the substations surveyed here, this cable is either buried approximately 0.5 m-1 m beneath the ground or placed in a trench covered with concrete, dielectric, or metal

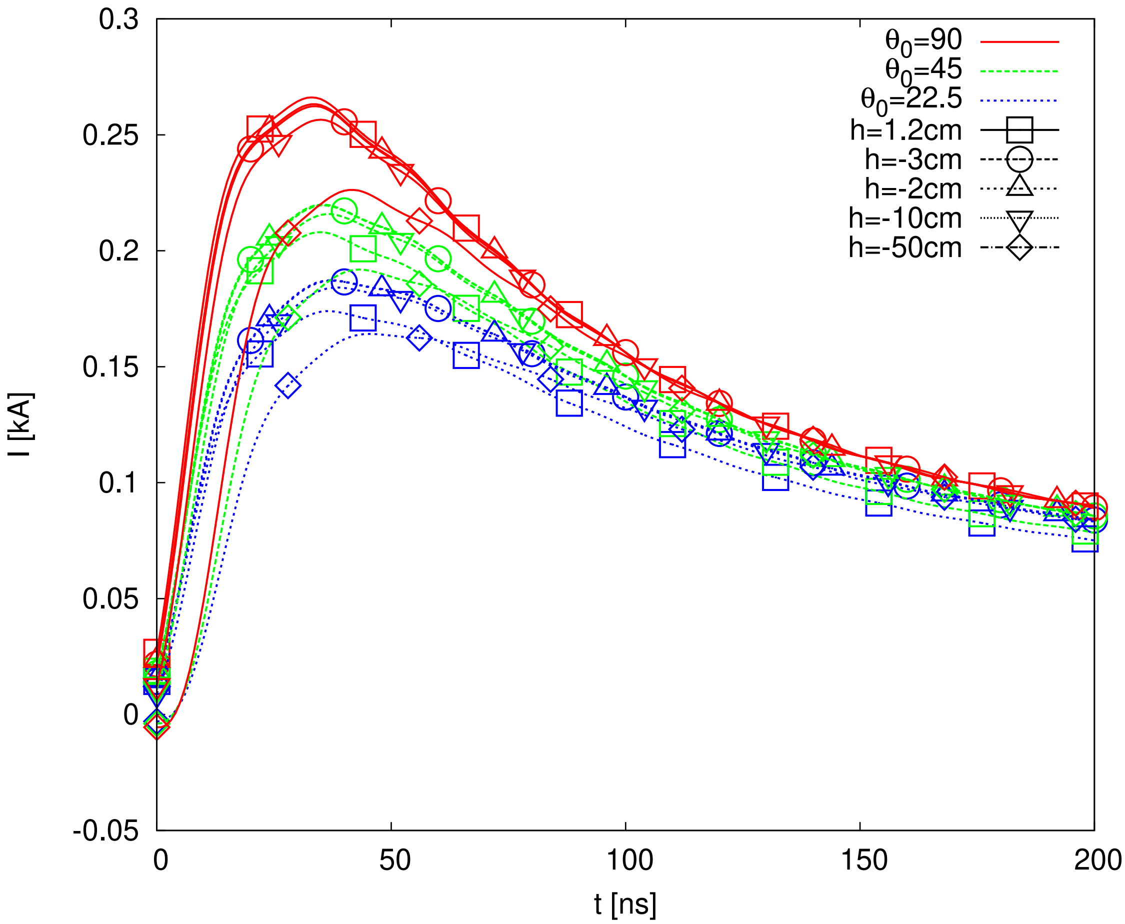


Figure 2.2.2. EMP coupling responses for various heights of cable as well as different angles of incidence. Note that line color gives incidence angle, while point marks indicate cable elevation h, a negative h meaning a buried cable (the marked points are staggered for visibility; their placement in t is not significant).

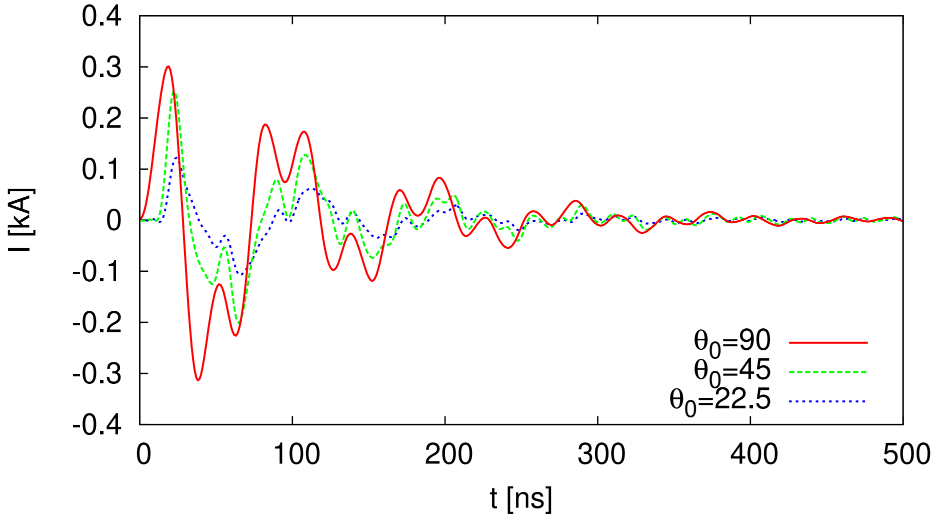


Figure 2.2.3. EMP coupling responses for elevated cable at different angles of incidence.

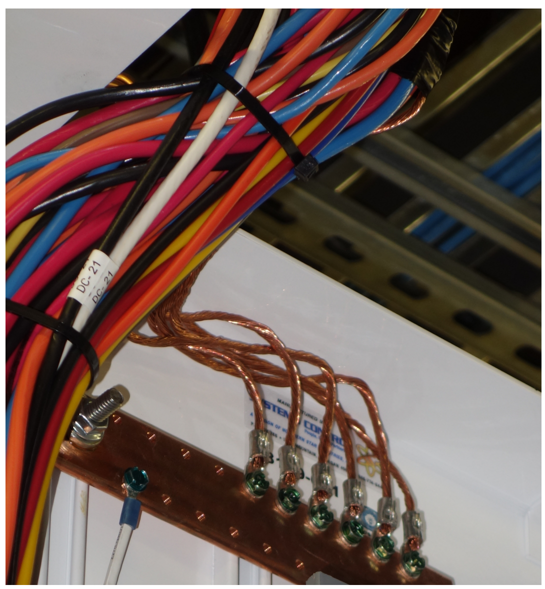


Figure 2.2.4. Cable shield pigtails in control shack in substation Layout 7.

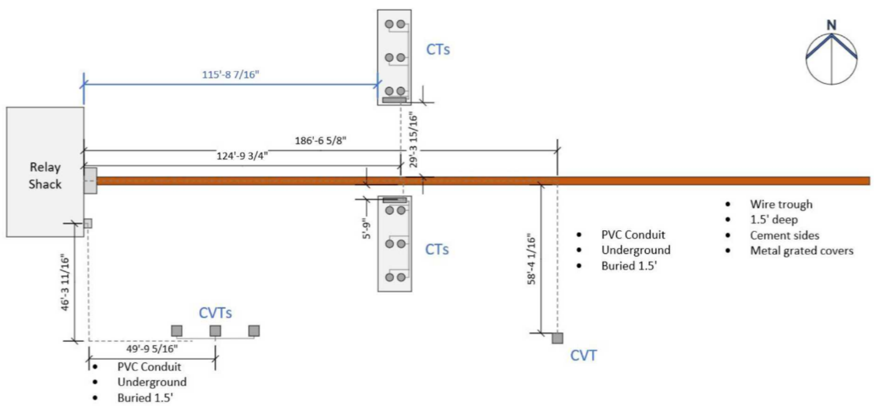
plates. A second cable segment runs horizontally between the end of the first segment and the instrument, and is either buried or elevated. In the case where the second segment is elevated, a third, vertical cable segment exists to connect between the two horizontal segments. Figure 1.0.2 shows an example of the second type of horizontal segment carrying cables to three potential transformers (PTs). The vertical connection between the elevated conduit and the buried cable can also be seen. Since a worst-case coupling is sought here, the cable connected to the instrument farthest from the buried line (in the case of Fig. 1.0.2 the instrument labeled "C") is simulated. In the diagrams and descriptions this segment is referred to as the cable connecting the instrument to the buried line or trench.

Since the modeling software used here does not handle vertical cables, any vertical cable segments are not included in the simulations. For reference, a simple analytical estimation of induced current at the point where such a cable enters the ground or trench is given in Appendix B. This estimation shows that the coupling to a vertical segment may be significant and even dominant in the case of an HEMP wave at grazing incidence (that is, traveling nearly parallel to the ground), and highlights a more detailed simulation of this coupling in conjunction with the connected horizontal lines as an important subject for future work. In the present study, however, a normally incident wave is considered, which maximizes coupling to the horizontal cables (according to the simulations shown in Section 2.2). The currents induced on a vertical line by a normally-incident wave are expected to be dominated by those induced on the horizontal cables, though here again further work with more sophisticated modeling tools may be needed to verify this at least in the case of more complicated cable configurations.

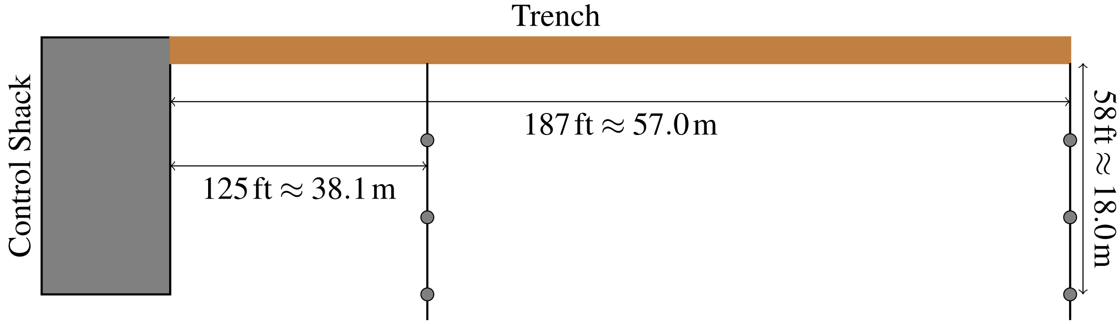
Since the ATLOG version used here can only simulate one horizontal line at a time, the coupling on the line between the instrument and the trench is calculated separately, without connection to the trench. Since maximum coupling is sought, the incident electric field is parallel to the conductor being analyzed. Moreover, because the wires in the trench are typically perpendicular to those running from the trench to the instruments, a maximum coupling for one implies zero coupling for the other. Because of this, the two wires can be simulated separately. For the simulations here, one main consequence of this separation is a neglect of the decay in the induced currents calculated at the trench entry point (labeled “B” and “C” in Fig. 2.6.1) during their propagation to the control shack (along AB or BC). In future work, calculation and incorporation of voltage and current decay estimations between the trench entrance and the control shack could give a more accurate prediction of the effects that actually reach the control house. In this work, however, no connection between or combination of the different cable segments is made in the simulations.

A further simplification must be made to the trench geometry itself. While the cable trench often travels in a straight line from the control shack, in some substations it will instead be made up of segments at right angles to each other. In such cases the longest and shortest cable segments that run in approximately straight lines are selected, and the HEMP effects calculated on each. To illustrate the simplifications made in the model, compare the plan view for Substation 1 in [8, Figure 2-1], reproduced in Fig. 2.3.1a, with the corresponding simplified Layout 4 in the present report, shown in Fig. 2.3.1b. In this case the simplified model does not differ dramatically from the actual layout with regard to the overhead geometry. By contrast, cable Layout 6 in this paper (diagrammed in Fig. 2.3.2b, corresponding to Substation 2 in [8, Figure 2-5] (reproduced in Fig. 2.3.2a), requires more drastic simplification. The longest instrument-to-trench run ($48\,\mathrm{ft} \approx 14.6\,\mathrm{m}$ in Fig. 2.3.2a) is carried over as well as the $79\,\mathrm{ft} \approx 24\,\mathrm{m}$ run from the control shack to the tee in Fig. 2.3.2a.

In addition, the ATLOG software used here requires an infinite, flat ground, and so wires in a trench are modeled as lying on top of the ground. This approach is considered suitable for three reasons. First, any error introduced by this approximation will tend to magnify the induced signal on the control wire, and worst-case coupling is sought here. Second, this error is probably small because the ground conductivity at the substations is low enough ($\approx 0.01\,\frac{\mathrm{S}}{\mathrm{m}}$ translating to a skin depth of meters even at megahertz frequencies) that little difference is observed between the

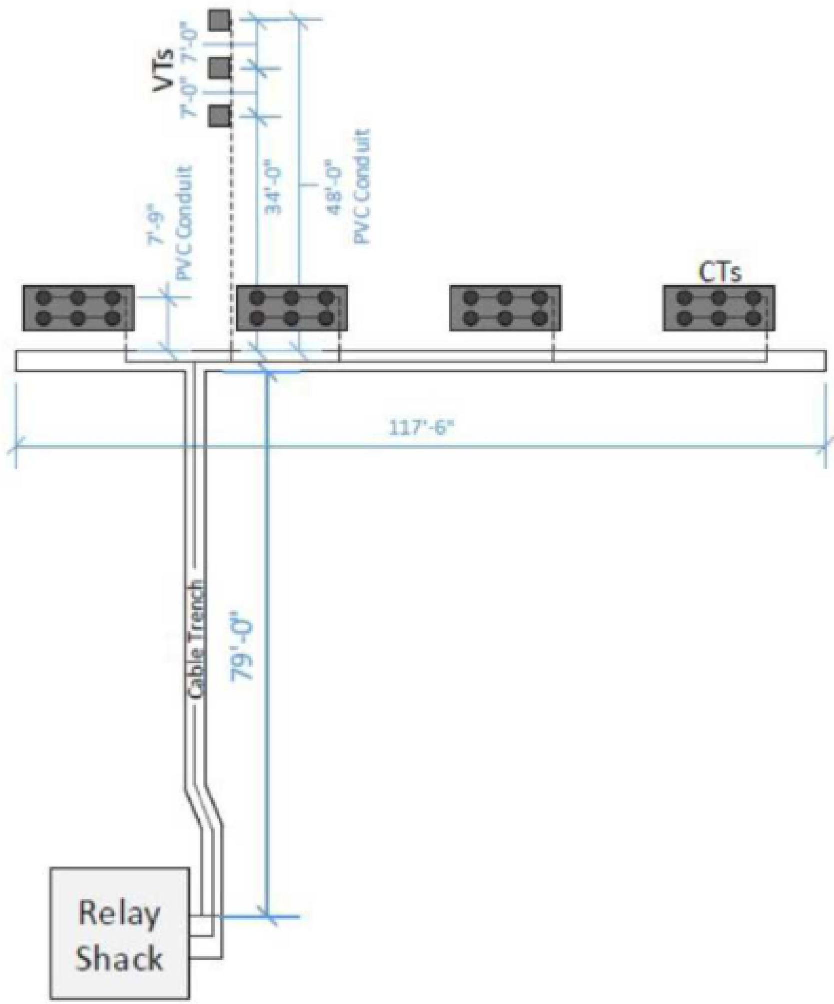


(a) Detailed plan view of Substation 1 in [8] (Layout 4 in this report).

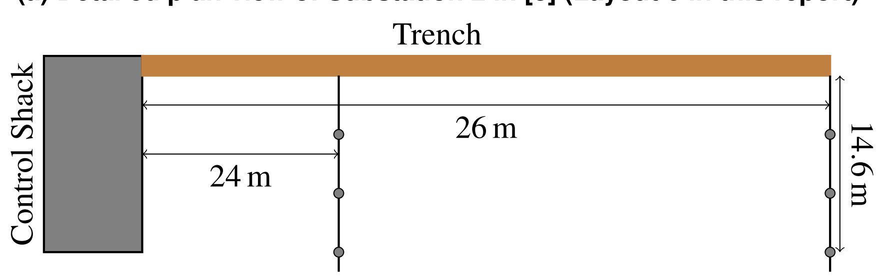


(b) Substation layout simplified for simulation.

Figure 2.3.1. Simplified Layout 4 compared to detailed substation geometry.



(a) Detailed plan view of Substation 2 in [8] (Layout 6 in this report).



(b) Substation layout simplified for simulation.

Figure 2.3.2. Simplified Layout 6 compared to detailed substation geometry.

response of a surface cable and a shallowly buried cable (compare simulation results below). Thirdly, as noted in [8], most substations have a layer of gravel spread over the switchyard. Since this gravel will tend to be a better insulator than soil, it effectively reduces the level of the conductive ground, thus reducing the effective depth of the trench. In other words, the depth of the trench will be smaller relative to the conductive ground than the depth of the trench relative to the insulating layer of gravel. In some substations, the trench is covered with a metal plate, which may provide more significant shielding, but further work is needed to quantify this shielding.

In connection with the previous point it should be noted that while substations typically have a metal grounding grid buried beneath the substation (as described in [8]), this is not modeled in ATLOG. All simulations here assume that return currents are entirely carried by the semi-infinite conductive ground.

The terminating impedance at each end of the cable used in the simulations is also simplified, being modeled either as an open circuit or as shorted to ground. In the case of unshielded cables this ignores the actual impedance of the device connected to the cable in the control shack as well as parasitic admittance to ground at the instrument in the control yard. The more sophisticated modeling required to capture these effects is beyond the scope of this report, and here the cable is simply treated as shorted to the ground at the control house termination (in order to estimate the maximum coupled current there) and as an open circuit at the termination in the control yard (i.e. the parasitic connection to ground is ignored). In the case of shielded cables the approximation as a short or open circuit is expected to reflect reality more closely, since in this case the current on a shield that is grounded or left open at each end is actually being simulated. It should be noted, however, that this approximation still excludes the effects of other cable segments attached to the cable under consideration.

As shown in Fig. 1.0.2, the elevation of the shorter horizontal cable segments can be significant compared to their length. In such cases, the ATLOG model uses terminating impedances as calculated in [11]. Note that these impedances do not represent physical lumped loads actually attached to the wire, but rather are corrections included in the model to account for effects of the larger height-to-length ratio, e.g. the capacitance between the wire and the ground. In some substations the cable is not elevated, and the termination away from the trench (i.e. where the cable connects to the instrument) is modeled as an open circuit or short circuit depending on the shield or cable there (always open for unshielded). In all cases the end near the trench is connected to an additional 100 Ω real resistance looking toward the control shack, approximating the characteristic impedance of the trench or buried transmission lines given by ATLOG.

2.4. HEMP E1 Waveform

The incident radiated environment is modeled using the IEC-61000-2-9 E1 HEMP double exponential waveform described in [3], The electric field amplitude $E(t)$ of this waveform is

$$E(t) = \begin{cases} KE_0 \left(e^{-\alpha t} - e^{-\beta t} \right) & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{2.1}$$

where $E_0 = 50\,\frac{\text{kV}}{\text{m}}$, $\alpha = 4\times10^7\,\frac{1}{\text{s}}$, $\beta = 6\times10^8\,\frac{1}{\text{s}}$, and $K = \left(e^{-\alpha t_{\max}} - e^{-\beta t_{\max}}\right)^{-1}$ with $t_{\max} = \log(\beta/\alpha)/(\beta-\alpha)$. The waveform has a 10 %-90 % rise time of about 2.5 ns, and a fall from peak to 50 % of peak of about 19 ns. The peak electric field is $50\,\frac{\text{kV}}{\text{m}}$.

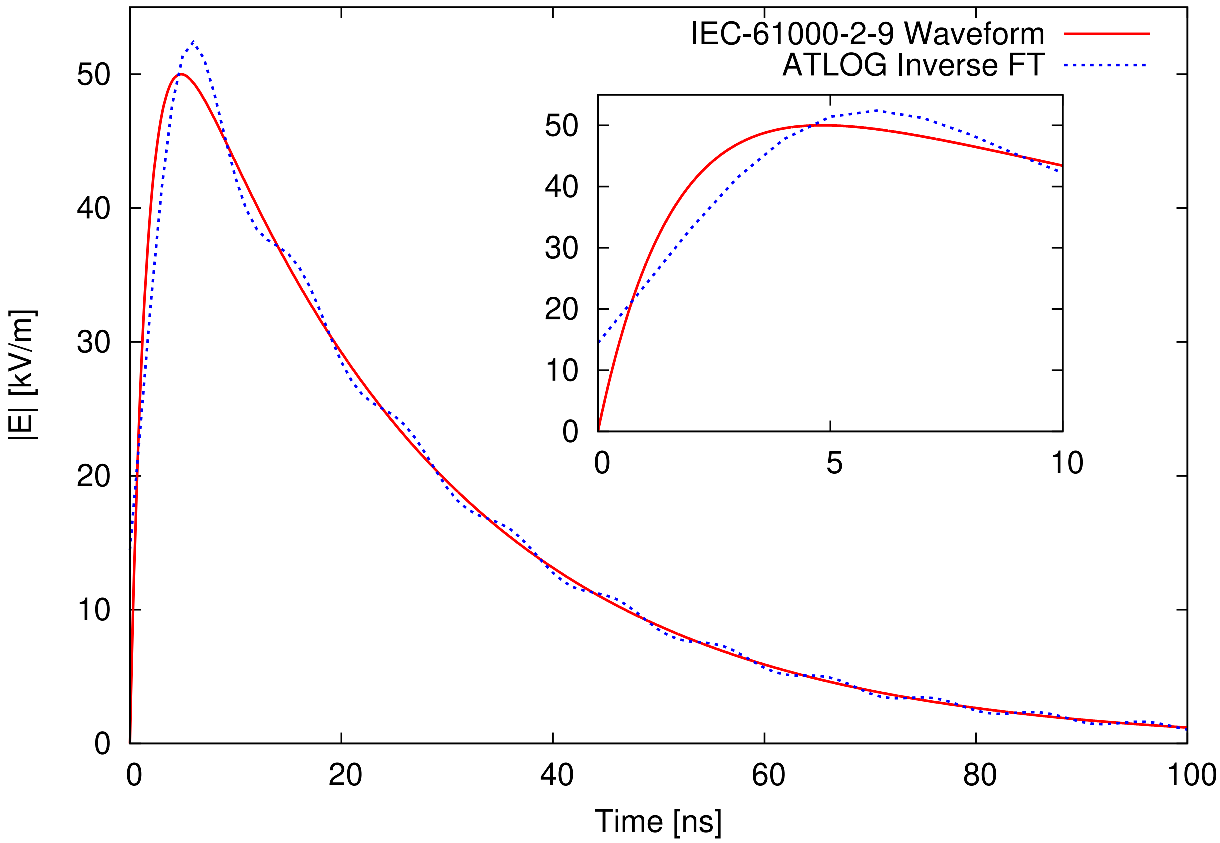


Figure 2.4.1. IEC-61000-2-9 waveform used in ATLOG's coupling calculations.

The waveform is plotted in Fig. 2.4.1. Note that since ATLOG performs a frequency-domain analysis a discrete Fourier transform is used to obtain the spectrum $E(\omega)$ used for coupling calculations. For reference, the inverse Fourier transform of $E(\omega)$ is also plotted in Fig. 2.4.1.

2.5. Cable Shields and Pigtail Ground Connections

As noted in the descriptions in Section 3, the different substations surveyed here showed a variety of cable shielding setups. Some used a copper mesh, others surrounded the bundle of inner conductors with parallel copper conductors, as shown in Fig. 2.5.1. Still others were entirely unshielded.

Because ATLOG cannot perform detailed modeling of shielded multi-conductor bundles, a cable is simplified to a single conductor in the simulation models. This is expected to be a good approximation for a well-shielded cable, such as those employing copper mesh with a high

Figure 2.5.1. Sparse wire shielding found at some substations.

optical coverage.The sparse stranded shielding shown in in Fig. 2.5.1 should be expected to be somewhat less effective. While a detailed analysis of the efficacy of different cable shields is beyond the scope of the present paper, a basic 2D full-wave analysis of a representative sparsely-shielded cable is shown in Appendix A, and suggests that this sparse shielding may provide some protection, although even in the idealized case considered there a significant portion of the induced current still flows on the inner conductors. The findings in Appendix A also suggest that modeling a multi-conductor cable as a solid conductor gives a reasonable approximation of the total current induced, though it should be remembered that asymmetries of the cable and configuration may result in a non-uniform distribution of the current among the individual conductors.

For shielded cables, the shielding conductor is connected to ground at one or both ends of the cable (as indicated in the parameter table for each layout in Section 3). For shielded cables in substations examined here this was done using a wire connected to the shield at one end and to a cabinet or bus bar at the other. This wire may even be formed by twisting the shield strands together. Shield grounding connections of this type are called **"pigtails"**. An example is shown in Fig. 2.2.4, and a simplified diagram is shown in Fig. 2.5.2.

After a center conductor leaves the shield, it forms a loop with the pigtail, grounding structure, and intervening circuitry. The magnetic field resulting from currents on the pigtail creates a voltage around this loop (see also [1]). For the pigtail-induced voltage calculations plotted for shielded cables in Section 3, the induced open-circuit voltage is calculated on a single center-conductor due to the pigtail current using the classical 2-wire inductance formula [9, 12]

$$M = \frac{\mu_0 \ell}{\pi} \cosh^{-1}\left(\frac{b}{2a}\right) \tag{2.2}$$

where μ_0 is the free space permeability, ℓ is the length of the pigtail running approximately parallel to the center conductor, b is the approximate average distance between the conductor and the pigtail, and a is the radius of the pigtail. The lengths b and ℓ are indicated in Fig. 2.5.2. The resulting voltage on the center wire termination (e.g. at point P in Fig. 2.5.2) is calculated using this mutual inductance multiplied by a forward-difference approximation of di/dt obtained from the ATLOG simulations. Since the focus here is on the open-circuit voltage induced on a center

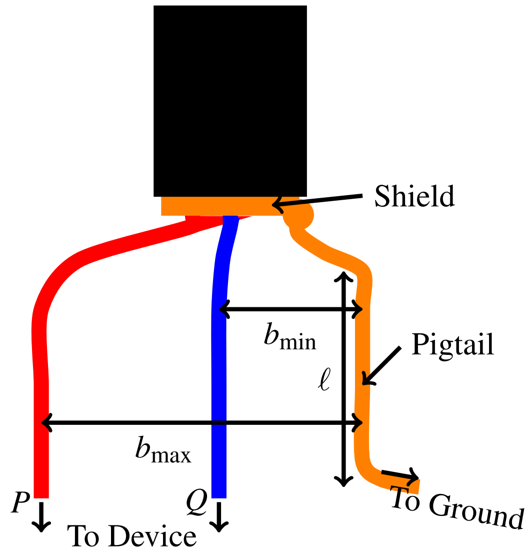


Figure 2.5.2. Pigtail geometry diagram. "Max conductor-to-ground induced voltage" in plots in Section 3 refers to voltage between point P and ground. "Max differential induced voltage" is between points P and Q.

conductor by a pigtail current, the interactions and mutual inductances of the center conductors with one another are ignored, and a center conductor/pigtail pair is treated as a two-wire system rather than part of a multi-conductor transmission line problem. Note that the formula (2.2) assumes that the majority of the coupling takes place along the parallel length ℓ, but this may not be the case depending on how the wires and pigtail are routed.

A given cable may carry several conductors, each of which will take a different path relative to the pigtail and consequently show a different induced voltage. This report focuses on the worst-case estimation of two voltages in particular. First, a wire-to-ground voltage exists between the center conductor and the chassis ground to which the pigtail is attached, and is plotted for each substation in Section 3 (except where the cable is not shielded) as the maximum pigtail inductance (due to the greatest effective distance between pigtail and center conductor) multiplied by di/dt. A differential voltage may also exist between two center conductors that lie at different distances from the pigtail. The differential voltages plotted in Section 3 are calculated as di/dt multiplied by the difference between the maximum and minimum mutual inductances M from a pigtail to the center conductors it shields, as estimated from photographs of the substation and using equation (2.2).

Note that the pigtail inductance will not exist where no shield is present, and for the substations in Section 3 where this is the case no induced voltage computation is shown, This does not mean that no terminal voltage is induced by the HEMP wave in such cases. Voltages will still exist on the unshielded wires with respect to ground but these effects are not included in the calculations. Differential voltages and currents may also be induced on the cable conductors due to asymmetries, but these are expected to be dominated by the common-mode effects.

Note also that at some substations the shielded cables are not grounded at the instrument in the control yard. As remarked in [8], this is done in order to avoid ground loops, but it may degrade the efficacy of the shield (see IEEE STD 11432012 [1]). Computing the extent of this degradation would require a much more detailed analysis of the cable layouts as well as more sophisticated modeling of the terminations than can be performed in the simulations run here, but the reader should be aware that such shields may still allow a substantial induced current on the instrument wires.

A shielded cable is modeled in ATLOG as a solid conductor whose radius is the same as that of the shield surrounding the cable. As noted above, simulations in Appendix A suggest that this will give a reasonable approximation of the total current on the cable, though a significant portion may in fact flow on the inner conductors rather than on the shield itself. The current induced on this conductor at the control shack termination is taken as the pigtail current. For unshielded cables, a worst-case current is still estimated by approximating the cable as a solid conductor. When the cable shield or the unshielded cable consists of several separate conductors, the radius of a cylinder passing approximately through the centers of the outermost conductors is estimated and used as the cable radius.

In addition to plotting the total current induced on a cable in Section 3, the plots also estimate a maximum current on individual instrument wires. For the conservative estimate given here, this is done not only for unshielded cables but also for shielded cables, since in many cases the shielding is sparse or not grounded at both terminations and so some coupling to the inner wires is to be expected. While the idealized simulation of symmetrical, infinite cables in Appendix A shows a fairly even division of the induced current among the center wires, asymmetries in the cable or surrounding environment may change this, and so a maximum center-conductor current is estimated by multiplying the total cable current by $N^{-1/3}$ where N is the number of center conductors, as recommended in [12]. In substations where different cables have different values of N, the cable with the smallest N is used.

In the case of well-shielded cables, a transfer impedance can be calculated to estimate the portion of the current induced on the inner conductors (see for example [7]). Since the focus in this report is on the pigtail-induced voltage for shielded cables, however, this calculation is not performed.

2.6. Comments on Diagrams

The simplified substation layouts modeled in Section 3 are depicted in simple plan-view diagrams of the substations. Note that these are not precise representations of the substation geometries, but only indicate the dimensions used for the highly-simplified ATLOG models. An explanation of the plan-view diagrams is illustrated in Fig. 2.6.1. As indicated, the main features of interest are the shortest (length AB) and longest (length AC) trench cable runs (in some cases they are directly buried cables rather than trenches) from the control shack into the yard as well as the longest observed line (whether buried or elevated) running from the trench (or buried cable) to the instrument (length CD in the diagram).

The transmission line models actually used in ATLOG are also shown for each substation as a cross-section diagram. For example, the model used to calculate coupling to the elevated cable shown in Fig. 1.0.2 is shown in Fig. 3.2.5. In cases where the model requires simplification (as in

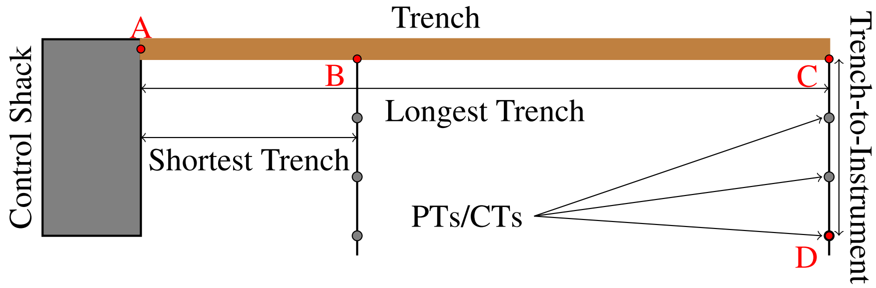


Figure 2.6.1. Substation plan-view sample with labels.

the case of a cable in a trench), the cross-section diagram shows the simplified model used in ATLOG. For instance, the coupling along the trench shown in Fig. 1.0.1 is calculated using the simplified model illustrated in Fig. 3.7.1.

3. SUBSTATION CABLE LAYOUTS AND SIMULATION RESULTS

In this section the simplified models and geometries of the various substation layouts surveyed are described, and the simulation results for the induced currents and, where applicable (i.e. in the case of shielded cables), pigtail-induced voltages, are plotted.

3.1. Substation Layout 1

This layout is based on dimensions for Substation 6 in [8], located in the Midwestern U.S. The instrument cables leaving the control shack are not run in a trench, but are buried directly approximately three feet below ground. They are are encased in PVC insulation but not shielded. For modeling in ATLOG, a bundle of four AWG #10 wires each with 1 mm of PVC insulation is approximated as a single conductor with 3.2 mm radius covered in a 1 mm radius coating. A diagram of the simplified layout used for simulation of this buried line is shown in Fig. 3.1.1. A 1.5 m-long horizontal cable elevated approximately 1.5 m above the ground travels between the buried line and the instrument (the vertical segment is not simulated here). The modeling dimensions used in ATLOG for simulation of this short elevated line are diagrammed in Fig. 3.1.2, and the dimensions used to estimate coupling along the elevated cable between the buried line and an instrument is shown in Fig. 3.1.5. Other physical parameters and simplifications used in the model are listed in Table 3.1.1.

The coupled currents simulated at the control-house terminations of the short and long buried cable lengths due to a normally incident wave with electric field parallel to the buried cable direction are plotted for the first 1 μs in Fig. 3.1.3 and Fig. 3.1.4, respectively. The simulated current flowing down from the elevated cable into the buried cable due to a normally incident wave with electric field parallel to the elevated cable is shown in Fig. 3.1.6. Note that while the length of the buried cable does not significantly affect the peak current induced, the current magnitude on the shorter buried length (current at A on AB in Fig. 3.1.1, plotted in Fig. 3.1.3) begins a more rapid decline than that on the longer cable at 400 ns, due to reflection. This behavior is a common trend among the buried or entrenched cables simulated for the substations surveyed in this paper, and is further discussed in Section 4.

Table 3.1.1. Model Parameters for Substation Layout 1

Parameter	Value
Wire Conductivity	$5.96 \times 10^7 \frac{S}{m}$
Ground Conductivity	$0.008 \frac{S}{m}$
Ground ε_r	20
Cable insulation ε_r	3.18
Min # Center Conductors/cable	4
Termination in switchyard	Open
Termination in shack	Short
Cable shield	None

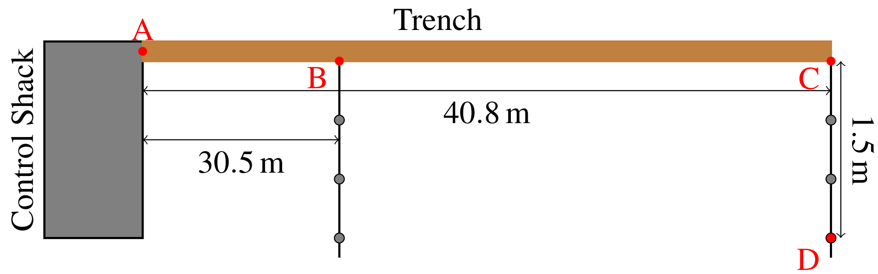


Figure 3.1.1. Substation diagram for Layout 1. Note: diagram not to scale; only shows min/max trench lengths simulated as well as max distance between trench and instrument as simulated.

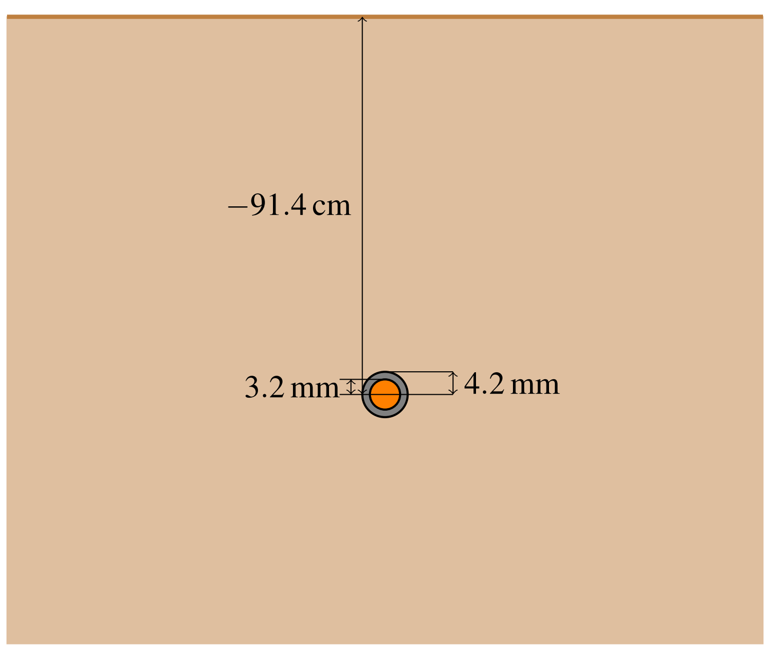


Figure 3.1.2. Buried cable Setup for Layout 1 (cable runs A-B and A-C in layout diagram). Note: Not to scale

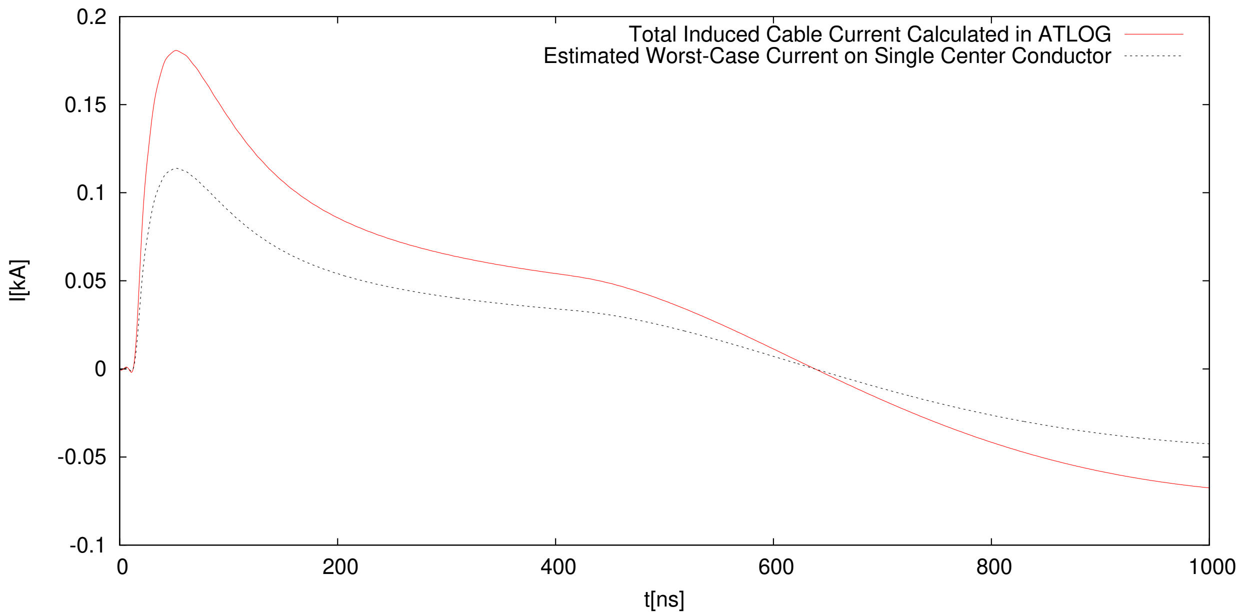


Figure 3.1.3. Currents induced on short buried cable for Layout 1. (Simulated measurements at point A due to coupling along length AB in Fig. 3.1.1.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5).

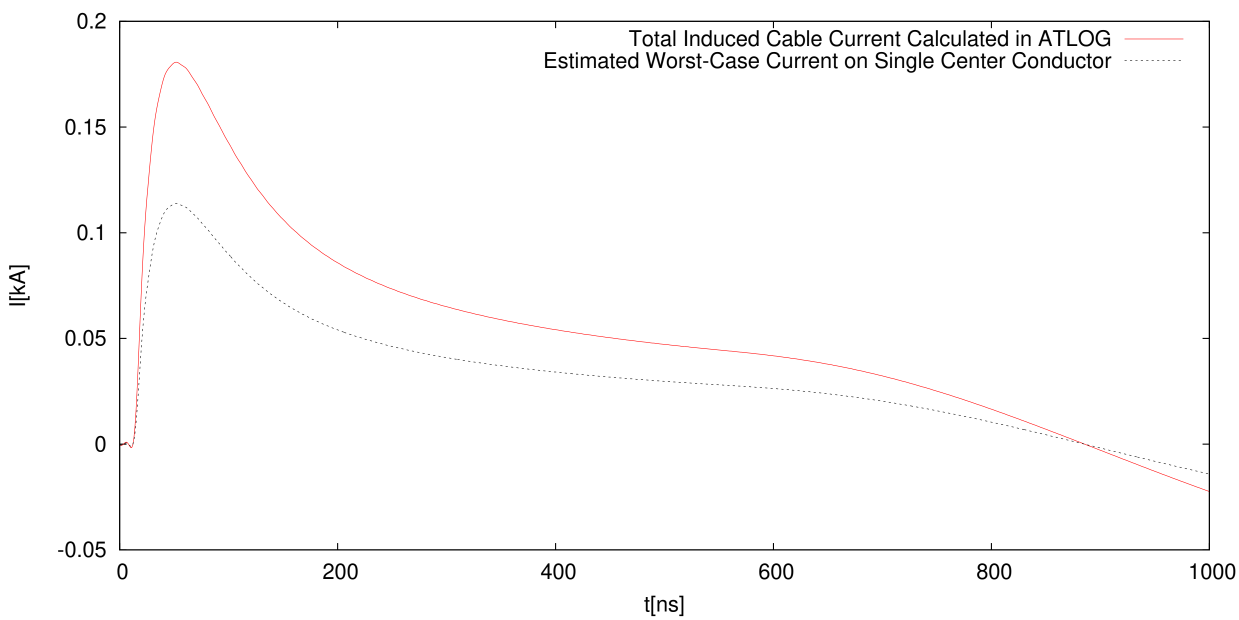


Figure 3.1.4. Currents induced on long buried cable for Layout 1. (Simulated measurements at point A due to coupling along length AC in Fig. 3.1.1.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5).

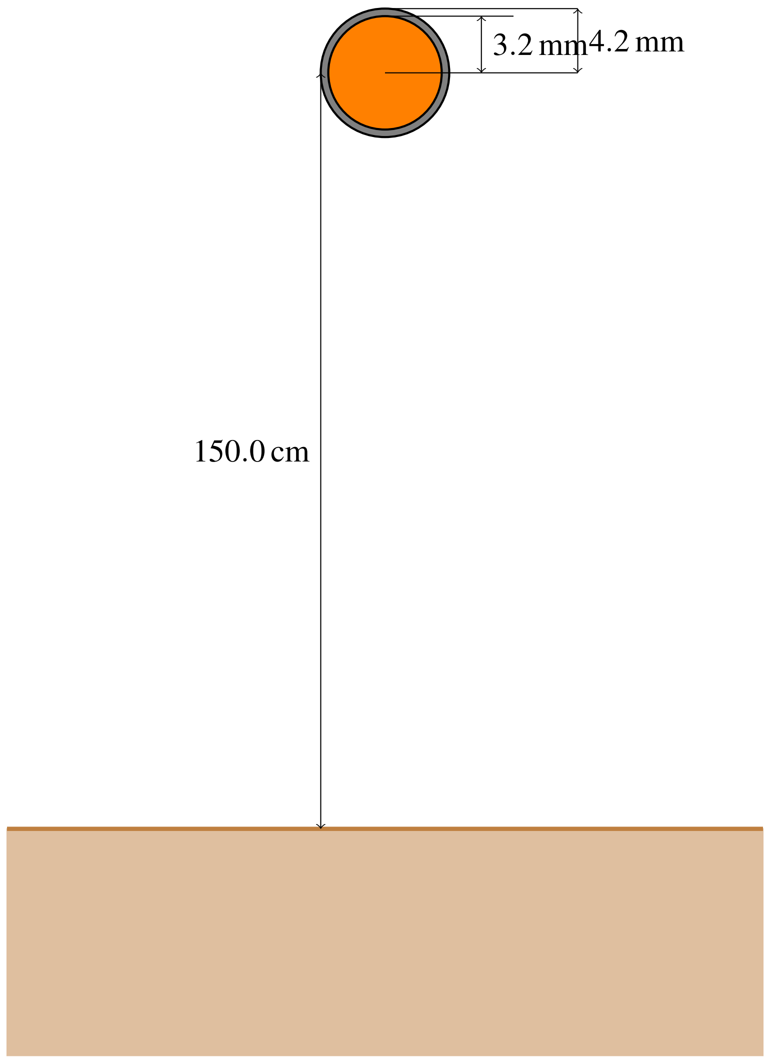


Figure 3.1.5. Cable between instrument and trench for Layout 1. Note: Not to scale

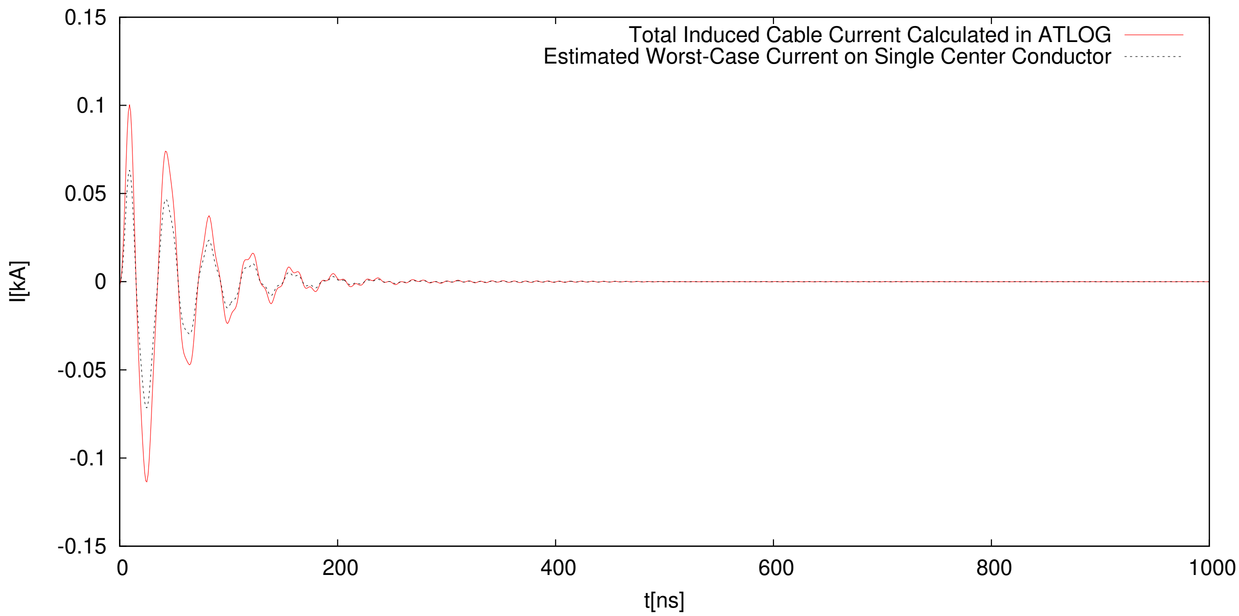


Figure 3.1.6. Currents induced on elevated instrument cable in Layout 1. (Simulated measurements at point C due to coupling along length CD in Fig. 3.1.1.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5).

3.2. Substation Layout 2

This layout is based on dimensions for Substation 5 in [8], which describes it as a small substation located in the Midwestern U.S. The instrument cables exit the control shack into a reinforced concrete trench, about 0.5 m deep (note that trench geometry is not modeled in ATLOG), and the trench is covered by removable concrete squares (also not modeled). The cable bundles are encased in PVC insulation but not shielded.

Basic simulation parameters and assumptions are shown in Table 3.2.1. An overhead diagram of the substation dimensions as simplified for the model is shown in Fig. 3.2.1. Coupling results to the shortest and longest cable runs in the trench (see Fig. 3.2.2 for simplified model used in ATLOG) are plotted in Fig. 3.2.3 and Fig. 3.2.4. Note the oscillatory behavior and rapid decay of the simulated current measured at the control shack termination. This is primarily due to the lengths of the trench cables, which are much smaller than those in the other substations. Similar behavior is noted in Fig. 3.2.6, in which is plotted the current on the horizontal cable connecting an instrument to the entrenched line. This 5 m horizontal segment is elevated 1.8 m above the ground (the ATLOG model for which is diagrammed in Fig. 3.2.5) and current is computed at the end where it enters the trench (point B or C in Fig. 3.2.1). Note the larger peak current in Fig. 3.2.6 (around 0.3 kA) compared to the peak current induced on the trench cables (≈ 0.18 kA).

Table 3.2.1. Model Parameters for Substation Layout 2

Parameter	Value
Wire Conductivity	$5.96 \times 10^7 \, \frac{S}{m}$
Ground Conductivity	$0.015 \, \frac{S}{m}$
Ground ε_r	20
Trench Cable insulation ε_r	4.0
Min # Center Conductors/cable	4
Termination in switchyard	Open
Termination in shack	Short
Cable shield	None

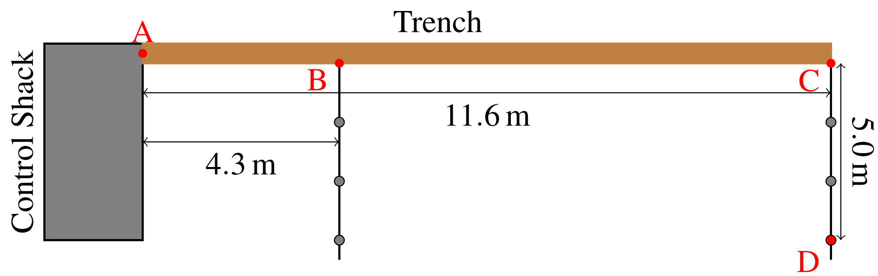


Figure 3.2.1. Substation diagram for Layout 2. Note: diagram not to scale; only shows min/max trench lengths simulated as well as max distance between trench and instrument as simulated. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

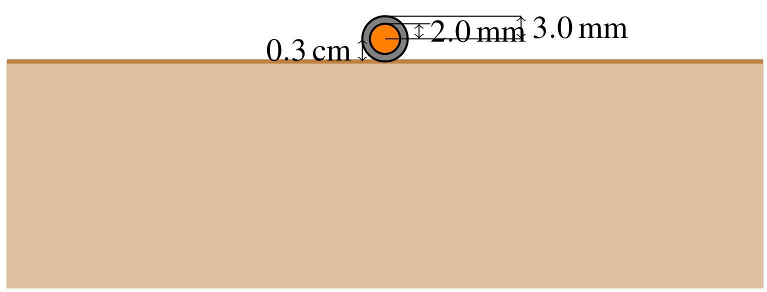


Figure 3.2.2. Trench Cable Coupling Setup for Layout 2. Note: Not to scale (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

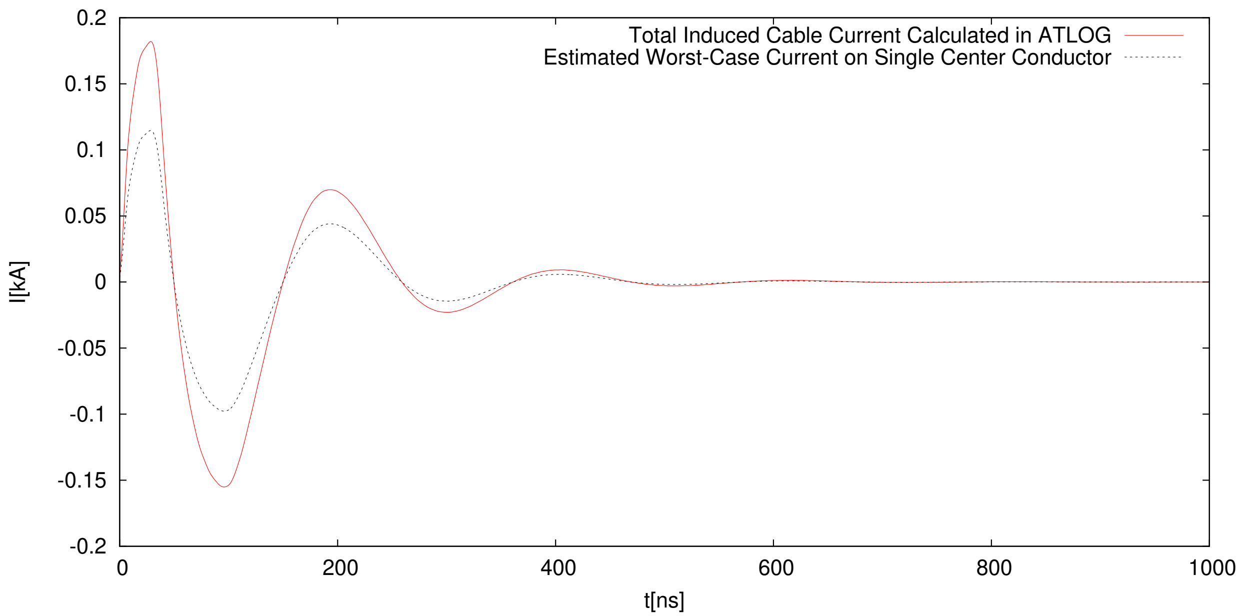


Figure 3.2.3. Currents induced on short trench cable for Layout 2. (Simulated measurements at point A due to coupling along length AB in Fig. 3.2.1.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

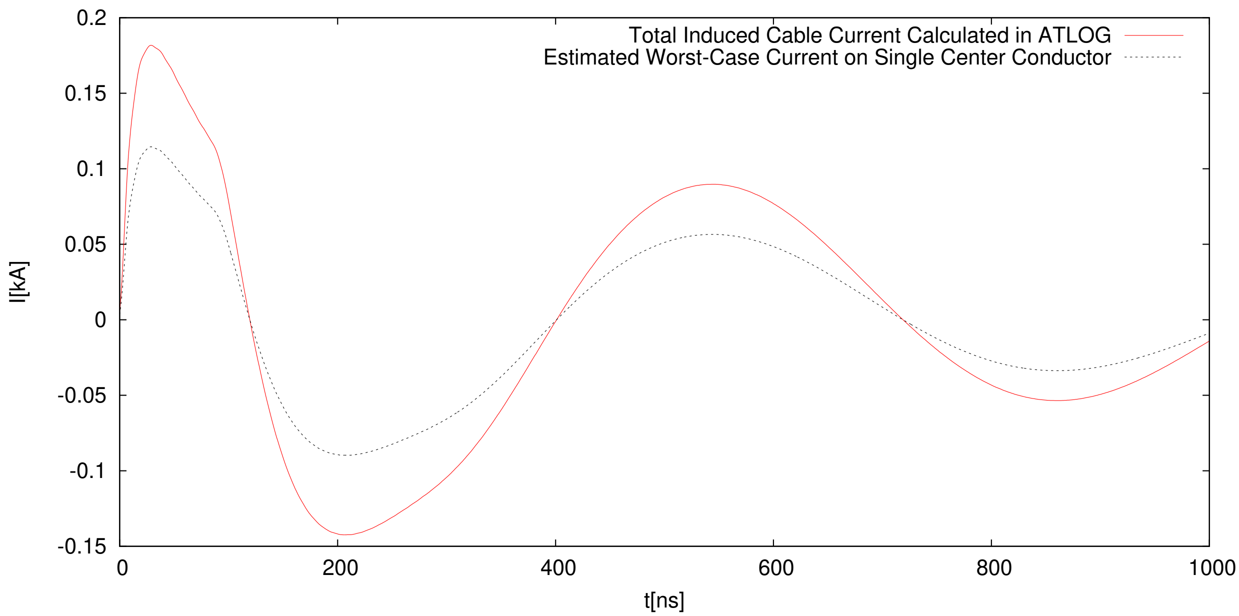


Figure 3.2.4. Currents induced on long trench cable for Layout 2. (Simulated measurements at point A due to coupling along length AC in Fig. 3.2.1.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

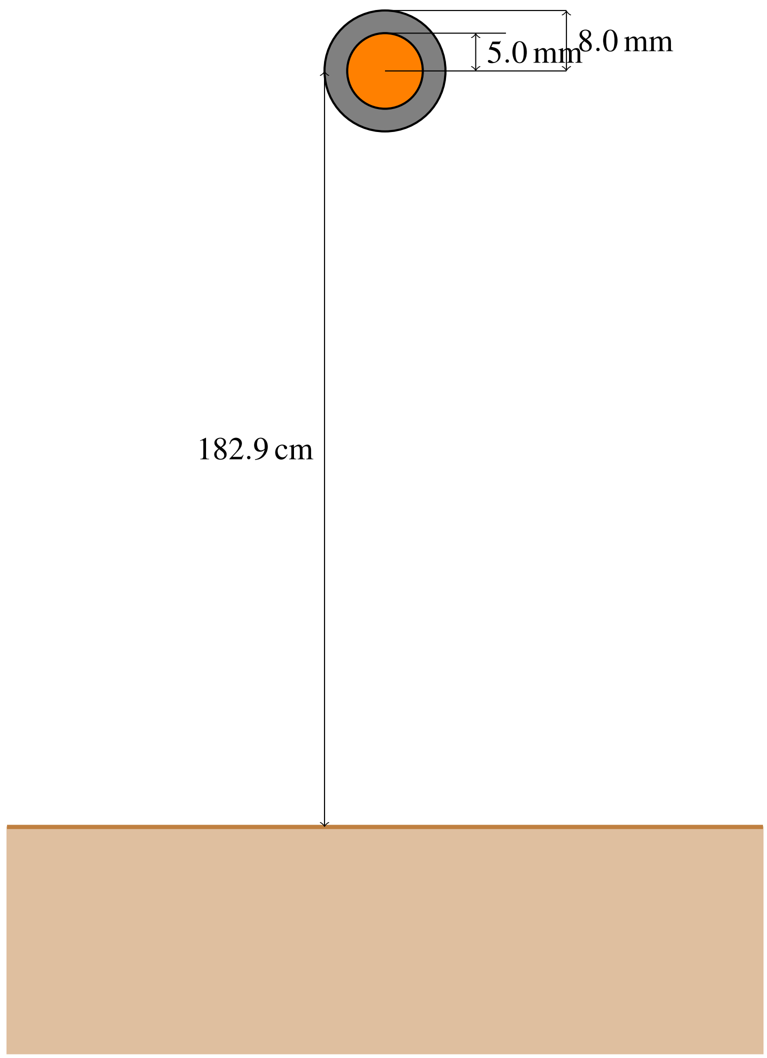


Figure 3.2.5. Cable between instrument and trench for Layout 2. Note: Not to scale

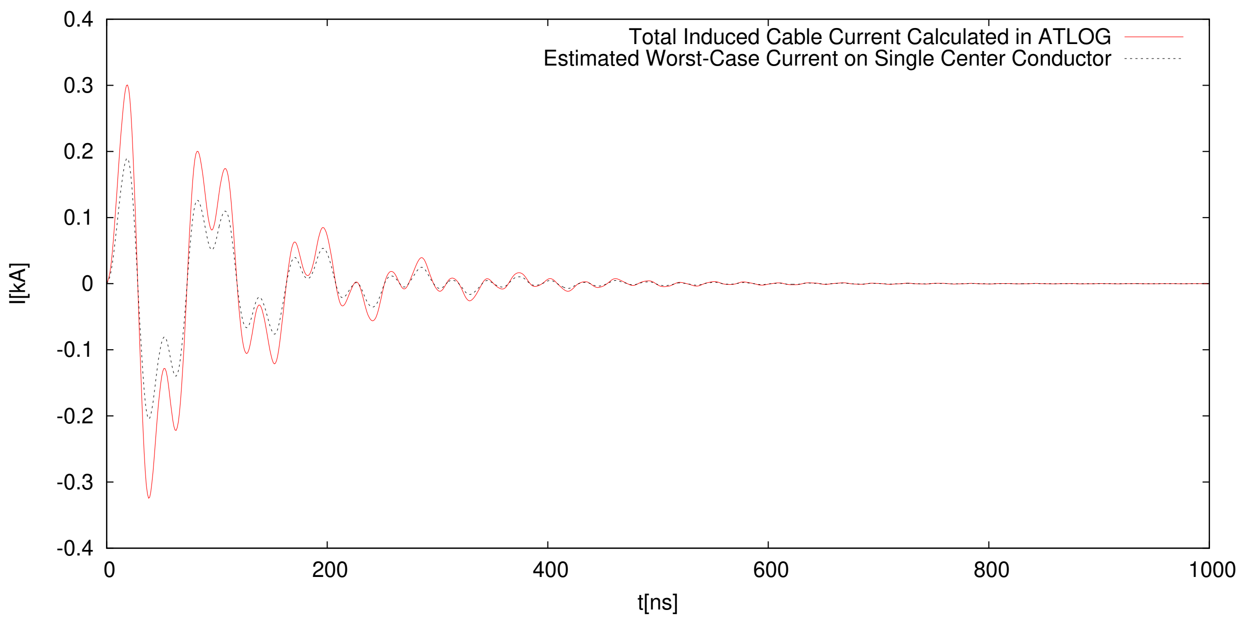


Figure 3.2.6. Currents induced on elevated instrument cable in Layout 2. (Simulated measurements at point C due to coupling along length CD in Fig. 3.2.1.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5).

3.3. Substation Layout 3

Cable Layout 3 is a simplification of the geometry in Substation 7 of [8], a transmission-level substation also located in the United States Midwest. The observed cables were unshielded and routed from the control house into the yard in PVC conduits approximately 3 feet below the ground. Near the instruments themselves, the cables exit the ground directly into elevated metal or metal flex conduits which carry them to the devices. The cable leaving the control shack is modeled here as a cable buried directly under 3 feet of conductive ground, as shown in Fig. 3.3.1. A notable feature of this layout is that the buried cable traveled over one hundred feet from the shack in a straight line, and then turned 90° and traveled nearly two hundred feet in an approximately straight line. The measurement devices were positioned in rows at right angles to the latter segment. The setup is diagrammed in Fig. 3.3.2. Coupling to each these segments is calculated at the end of the segment nearest to the shack, that is, current induced by a parallel, normally-incident E1 pulse on segment BC was calculated at B (see Fig. 3.3.4), and the current induced by a parallel, normally incident pulse on AB was calculated at A (see Fig. 3.3.3). In the former case (coupling to BC) the termination at B is treated as a short circuit to ground, while in the latter case (coupling to AB) the termination at B is treated as an open circuit. Note that the current at B due to coupling on BC will be attenuated by the time it reaches A.

Since the cable is unshielded, a cable bundle of 4 AWG #9 conductors is modeled as a single conductor with a radius of 3.5 mm with a 2 mm PVC coating with dielectric constant $\varepsilon_r = 3.18$.

A 5 m-long cable elevated 2.4 m off the ground connects potential transformers to the far end of the buried cable (C in the diagram). The connection is at the center of the elevated line. In reality, the elevated cable is contained in metal conduit but is carried to the ground by a PVC conduit. The effects of this conduit with its various connections to the metal structures supporting the measurement instruments are beyond the simulation capabilities of the tools used here, and so the coupling to a 2.5 m length of elevated cable is simulated, using the model in Fig. 3.3.5, that is open at one end and shorted to ground at C, where the current is computed and plotted in Fig. 3.3.6. This is included for completeness, but the reader should be aware that more sophisticated modeling techniques will be required for a precise estimation of the induced currents. Note also that, once again, the induced signal plotted in Fig. 3.3.6 reaches a slightly higher current peak than the buried lines (0.16 kA vs. 0.13 kA), though the former is also highly oscillatory due to reflections, decays rapidly in time, and will likely experience some additional attenuation as it travels to the control house.

Material and model parameters not shown in the diagrams are listed in Table 3.3.1.

Table 3.3.1. Model Parameters for Substation Layout 3

Parameter	Value
Wire Conductivity	$5.96 \times 10^7\ \frac{\mathrm{S}}{\mathrm{m}}$
Ground Conductivity	$0.015\ \frac{\mathrm{S}}{\mathrm{m}}$
Ground ε_r	20
Trench Cable insulation ε_r	3.18
Min # Center Conductors/cable	4
Termination in switchyard	Open
Termination in shack	Short
Cable shield	None

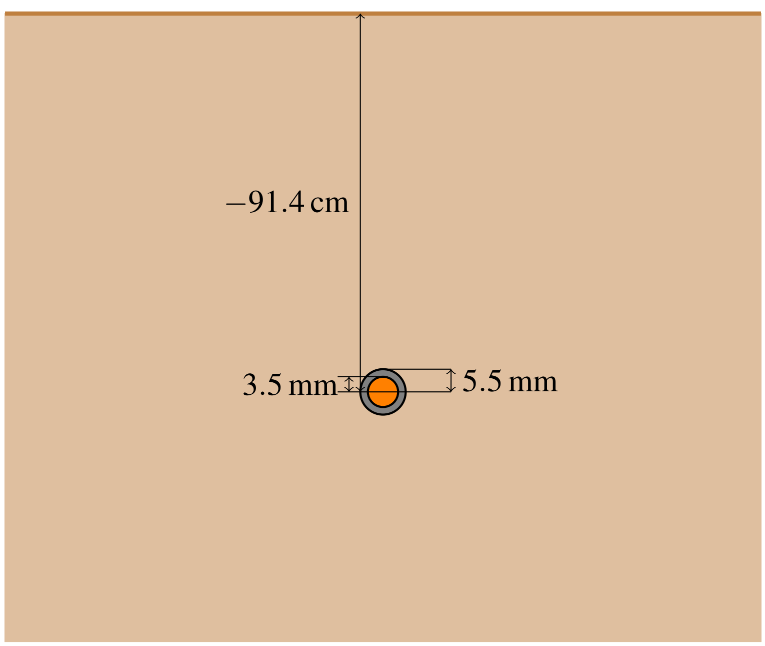


Figure 3.3.1. Buried Cable Model for Layout 3. Note: Not to scale.

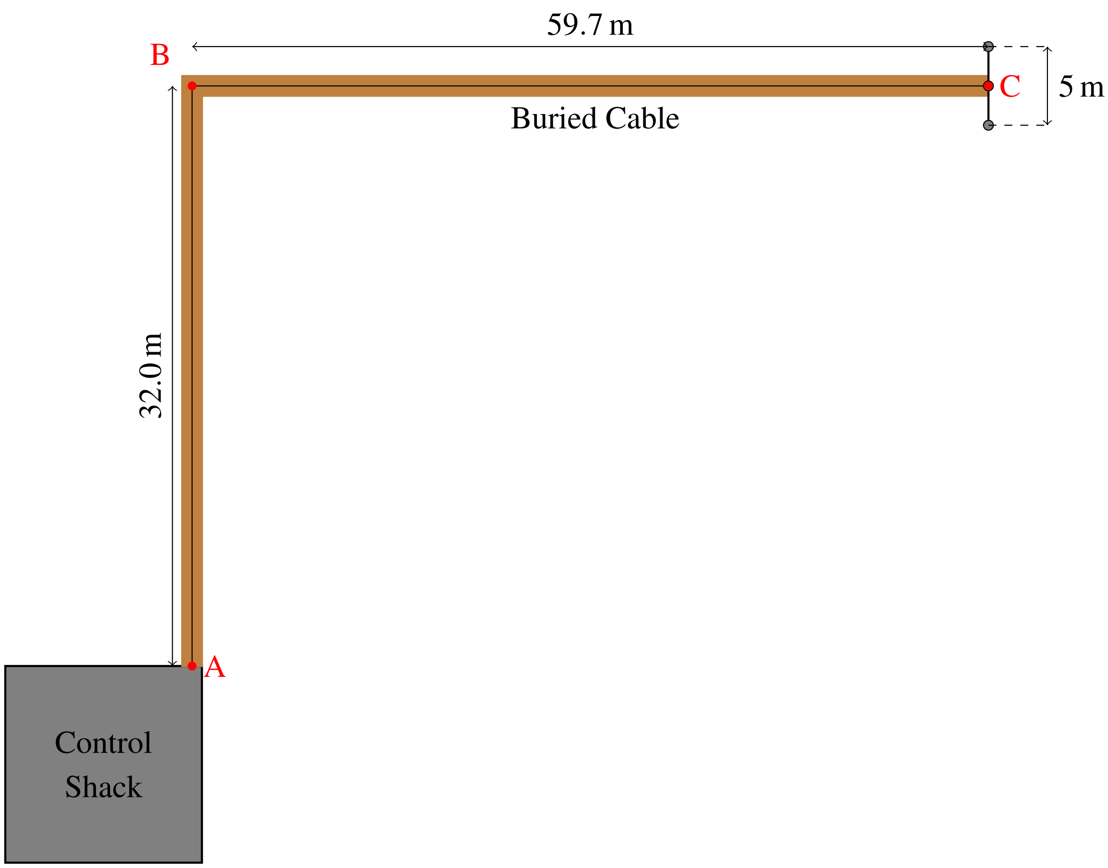


Figure 3.3.2. Substation diagram for Layout 3. Note: diagram not to scale.

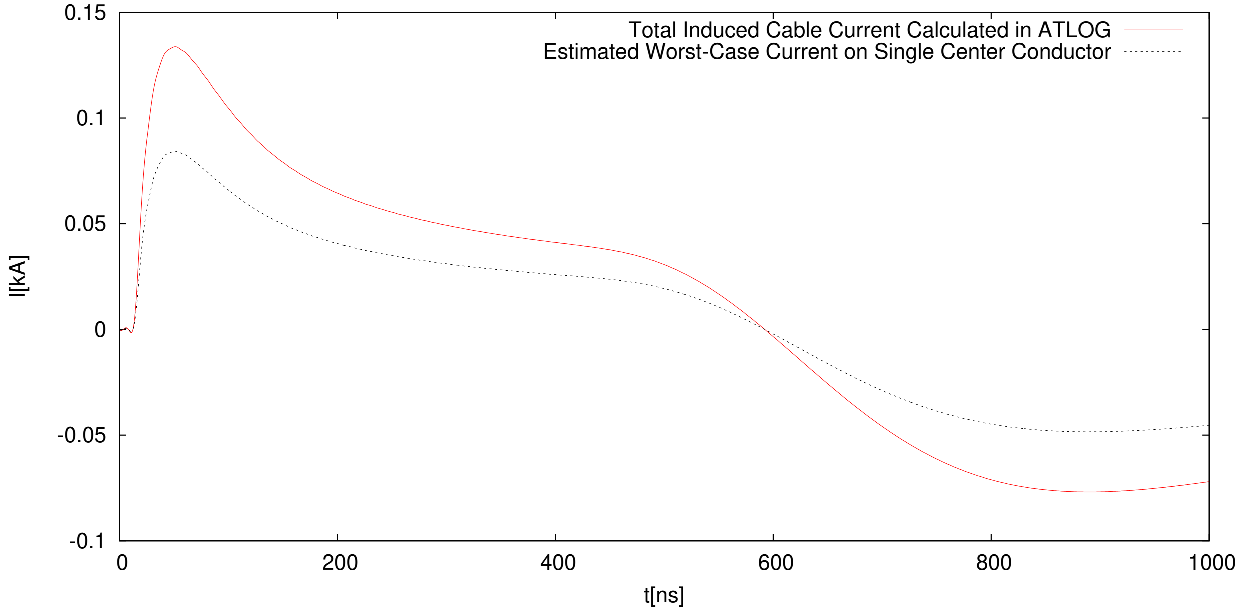


Figure 3.3.3. Currents induced on long buried cable for Layout 3. (Simulated measurements at point A due to coupling along length AB in Fig. 3.3.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5).

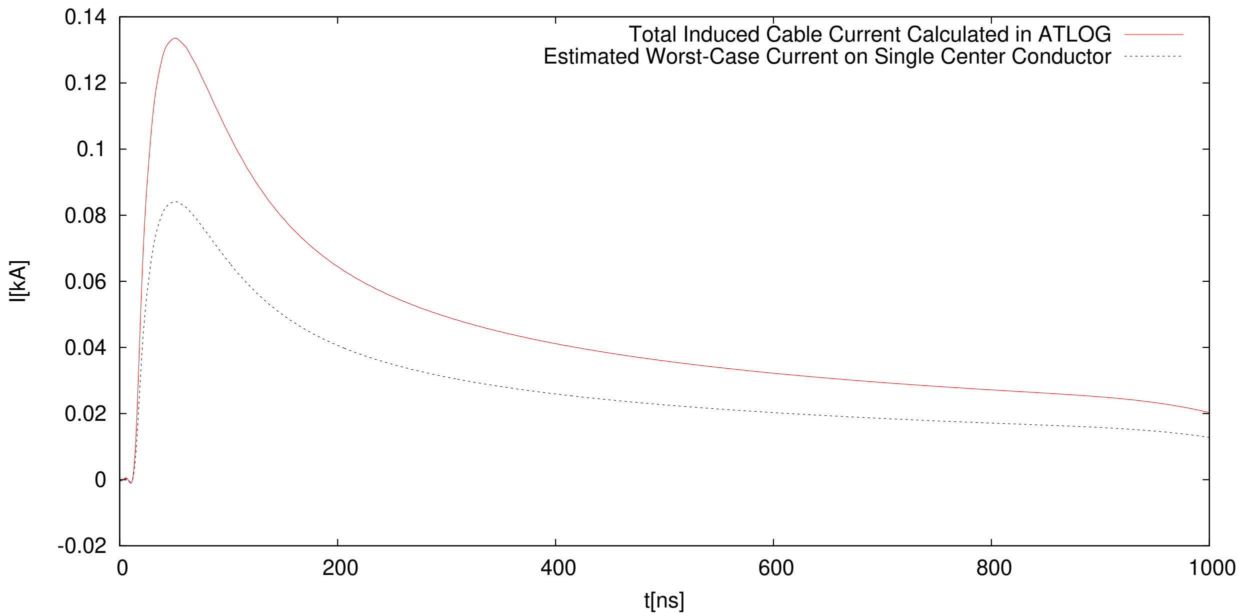


Figure 3.3.4. Currents induced on long buried cable for Layout 3. (Simulated measurements at point B due to coupling along length BC in Fig. 3.3.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5).

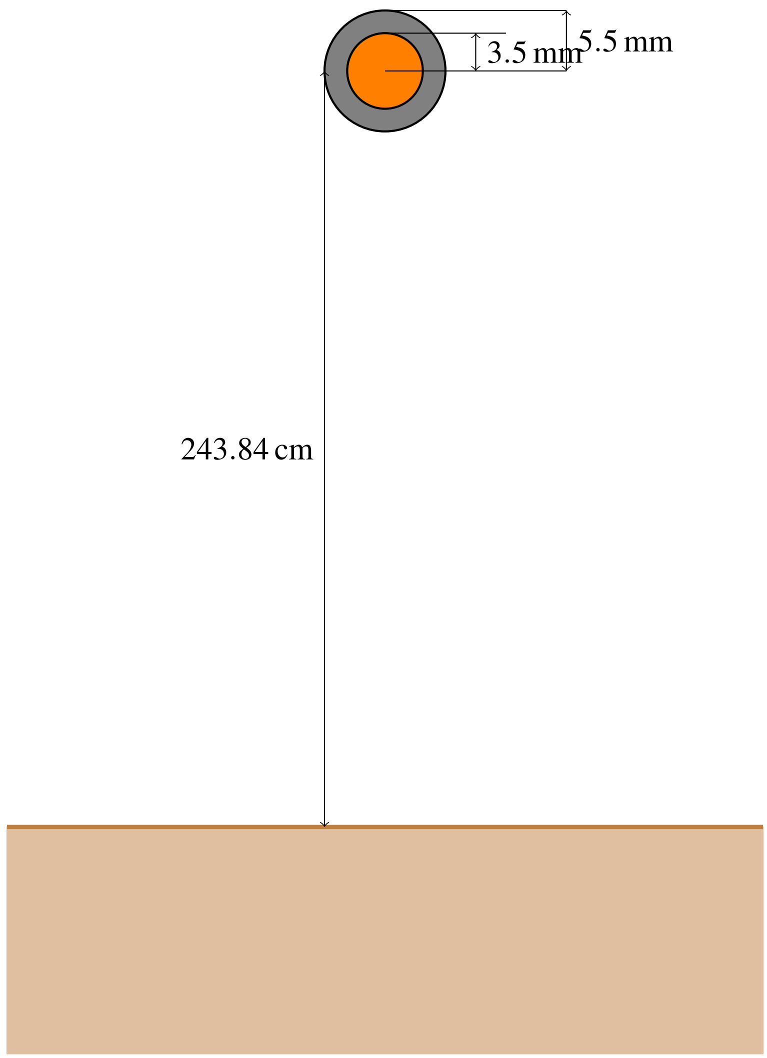


Figure 3.3.5. Cable between instrument and trench for Layout 3. Note: Not to scale

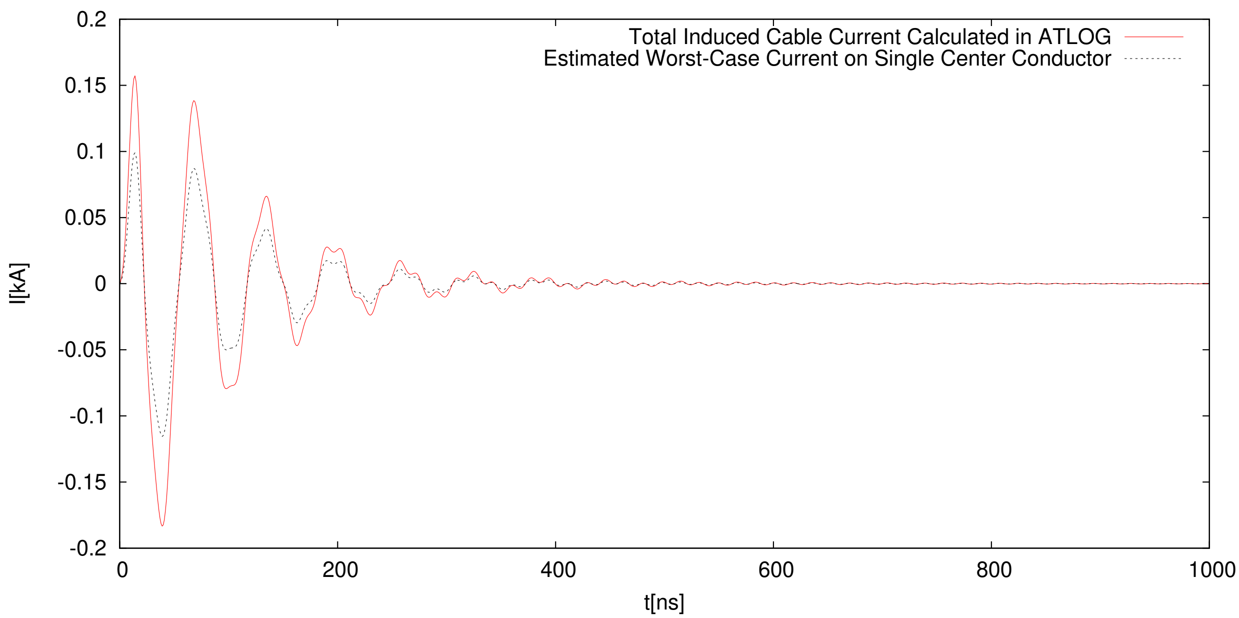


Figure 3.3.6. Currents induced on elevated instrument cable in Layout 3. (Simulated measurements at point C in Fig. 3.3.2 due to coupling on half of $5\,\mathrm{m}$ elevated cable.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5).

3.4. Substation Layout 4

Cable Layout 4 is based on a substation in the southwestern U.S., described in [8, Section 2.1]. The control cables travel in bundles through a concrete trench ($\approx 0.5\,\text{m}$ deep) covered by corrugated steel. The bundles are shielded (shielding type not disclosed) and the shield is protected by PVC. The shields have pigtail grounding in the control shack; the opposite termination of the shield (in the control yard) is left open to prevent ground loops.

The cable lengths for this layout are labeled in the plan view in Fig. 3.4.2. The ATLOG model and dimensions for the cables in the trench are shown in Fig. 3.4.1, and the coupling to the shortest and longest trench cables is plotted in Fig. 3.4.3 and Fig. 3.4.4, respectively. Note the high voltages ($\approx 16\,\text{kV}$) induced on the center conductors due to the current on the pigtail in the control house.

The ATLOG model used for the buried cable between the trench and the instruments is diagrammed in Fig. 3.4.5, and the resulting coupling (current at C due to normally incident E-field parallel to CD) is shown in Fig. 3.4.6. Other modeling parameters and assumptions are shown in Table 3.4.1.

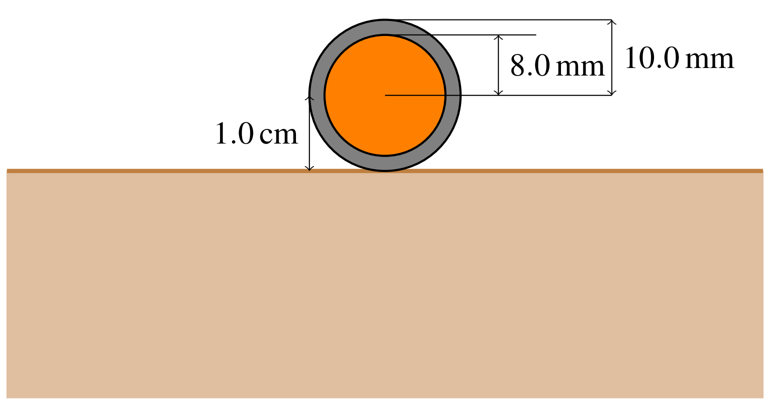


Figure 3.4.1. Trench Cable Coupling Setup for Layout 4. Note: Not to scale (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

Table 3.4.1. Model Parameters for Substation Layout 4

Parameter	Value
Wire Conductivity	$5.96 \times 10^7 \frac{S}{m}$
Ground Conductivity	$0.015 \frac{S}{m}$
Ground ε_r	20
Trench Cable insulation ε_r	3.18
Min # Center Conductors/cable	4
Cable shield termination in switchyard	Open
Cable shield termination in shack	Short
Pigtail Length	0.5 m
Pigtail Radius	2.6 mm
Pigtail Distance from Conductor	0.6 cm-15 cm
Conductor radius	2.6 mm

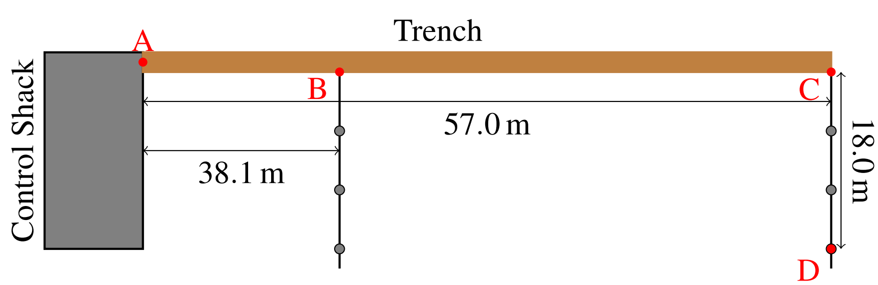


Figure 3.4.2. Substation diagram for Layout 4. Note: diagram not to scale; only shows min/max trench lengths simulated as well as max distance between trench and instrument as simulated. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

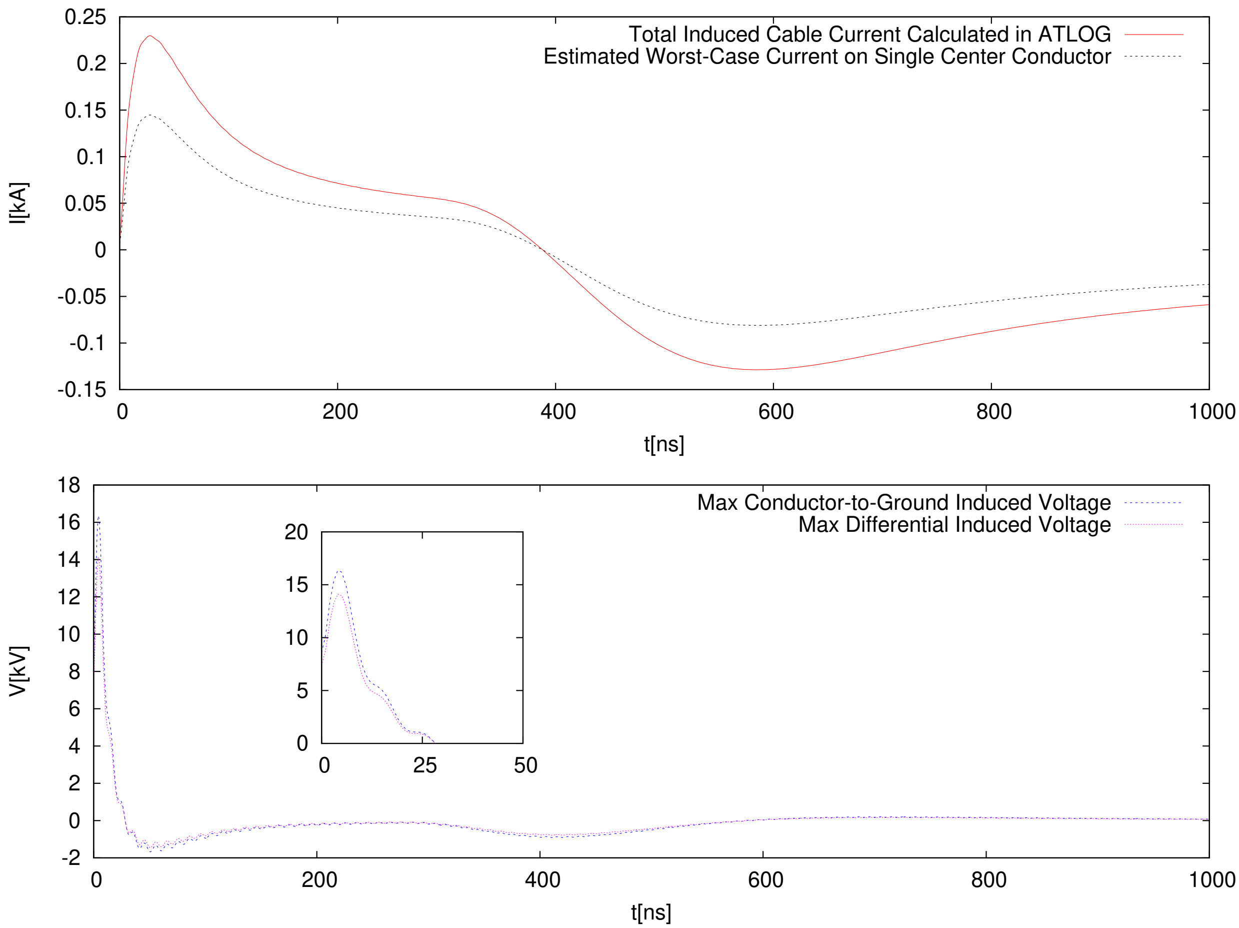


Figure 3.4.3. Currents and voltages on short trench cable for Layout 4. (Simulated measurements at point A due to coupling along length AB in Fig. 3.4.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

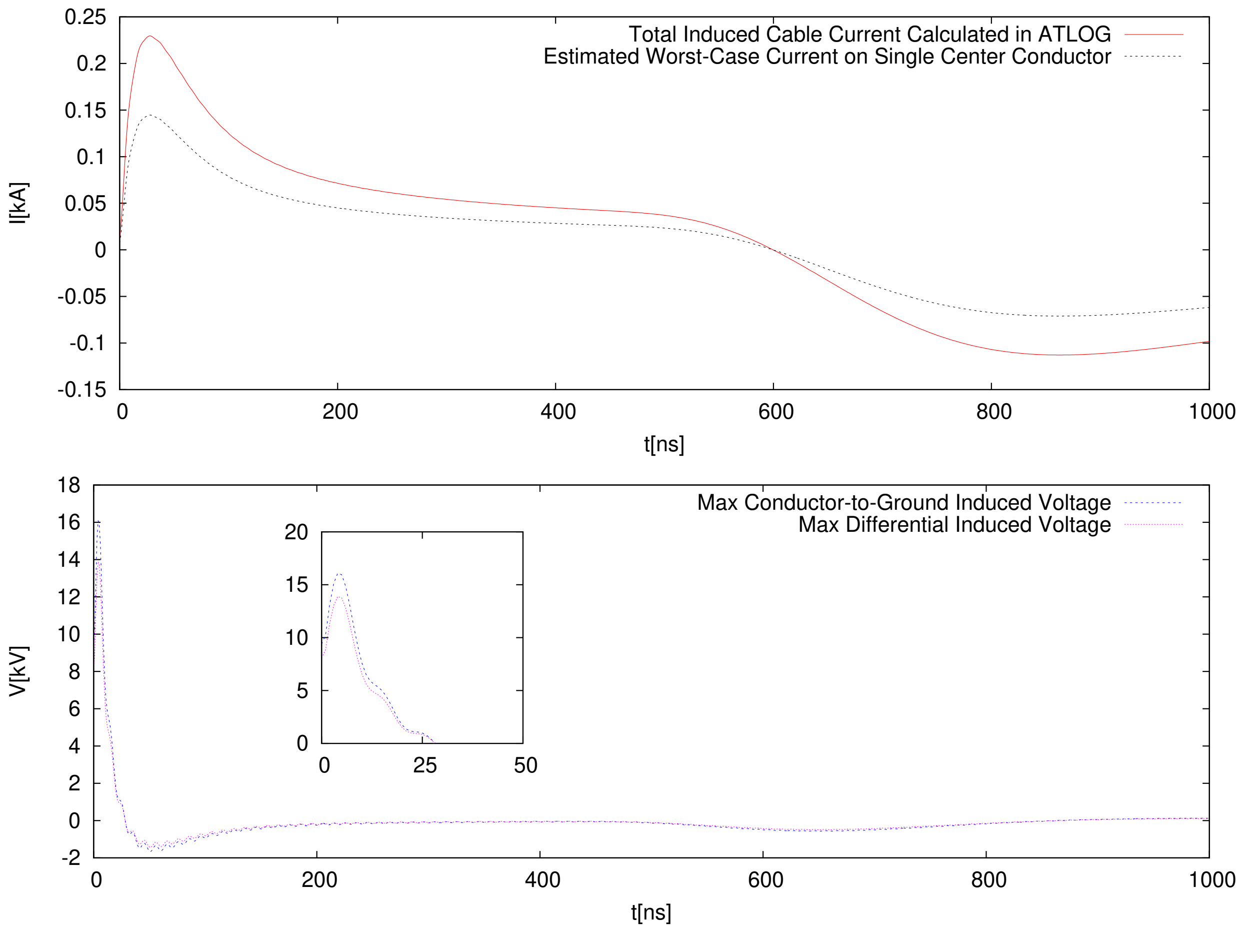


Figure 3.4.4. Currents and voltages on long trench cable for Layout 4. (Simulated measurements at point A due to coupling along length AC in Fig. 3.4.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

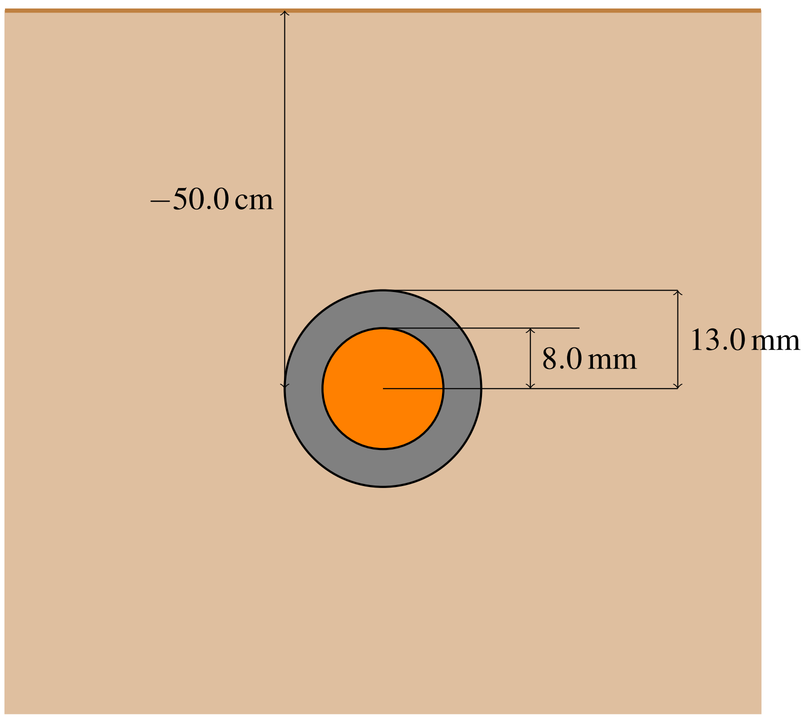


Figure 3.4.5. Cable between instrument and trench for Layout 4. Note: Not to scale

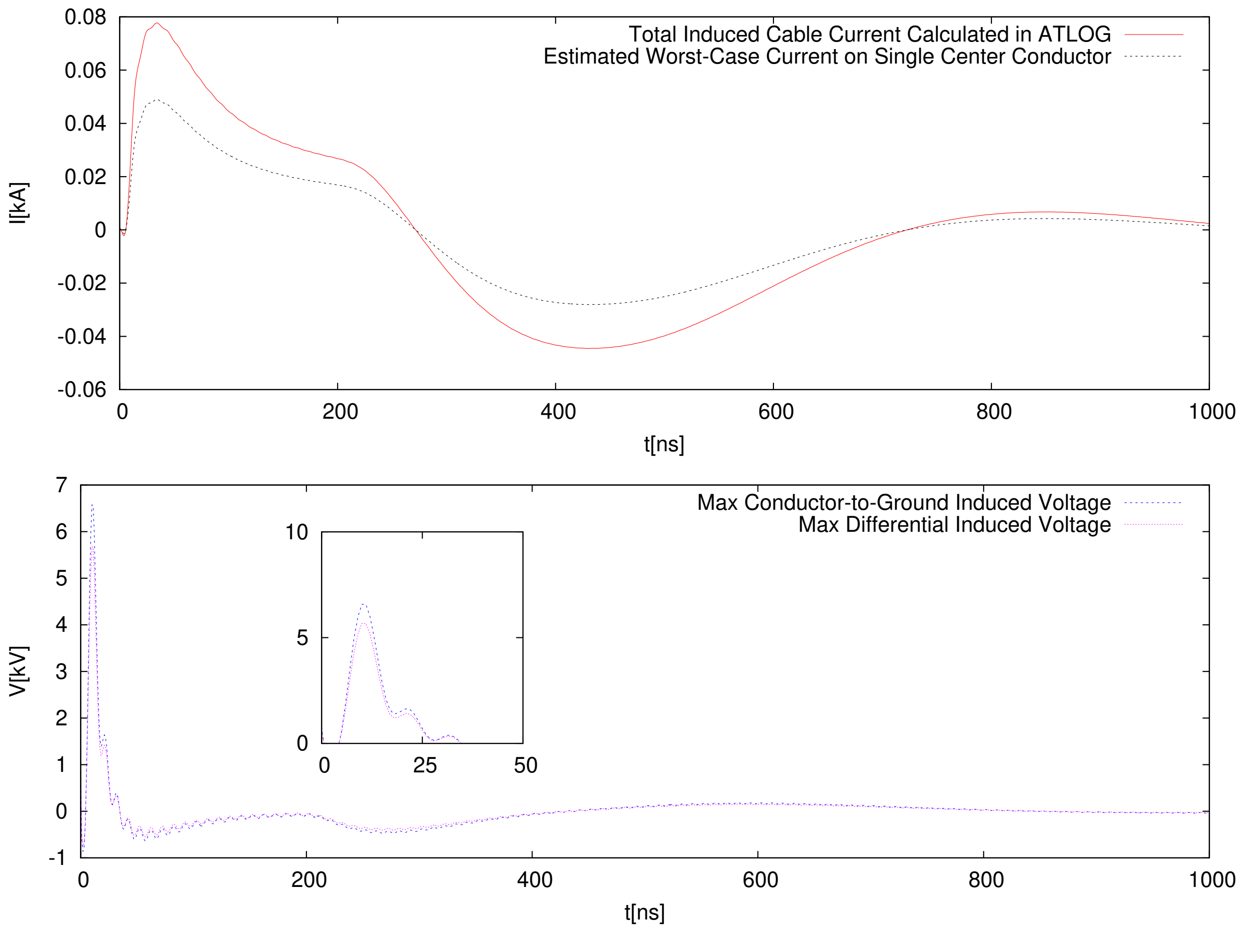


Figure 3.4.6. Currents and voltages on buried instrument-to-trench cable in Layout 4. (Simulated measurements at point C due to coupling along length CD in Fig. 3.4.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2.

3.5. Substation Layout 5

Cable Layout 5 follows the setup of a substation in the Midwestern U.S., documented in [8, Section 2.4]. The cables are buried approximately 0.5 m below the ground in PVC conduits. The coupling plotted in Fig. 3.5.3 and Fig. 3.5.4 is for the cables buried directly in the ground, as shown in Fig. 3.5.1. The cables are shielded by a copper mesh which is grounded both at the control shack and at the instrument box itself. In order to simplify for ATLOG, the buried cable lengths AB and AC in Fig. 3.5.2 are treated as grounded at points B and C respectively.

Coupling to the short buried segment connecting to the instrument (line CD in the plan view) is calculated in ATLOG using the model diagrammed in Fig. 3.5.5, and the results are shown in Fig. 3.5.6. The cable is modeled as shorted to ground at the instrument end (point D in the diagram). Table 3.5.1 lists other basic model parameters and assumptions.

Note that the estimated induced pigtail voltage in Fig. 3.5.3, Fig. 3.5.4, and Fig. 3.5.6 is much smaller (peaking at less than 1 kV) than that calculated for other layouts, due to the short length (given in Table 3.5.1) of wire and pigtail running parallel (ℓ in Fig. 2.5.2), the small distance between them (b in Fig. 2.5.2), and in part the cable burial depth. The differential voltage (colored magenta in the figures) is also much smaller than the maximum conductor-to-ground voltage (colored dark blue in the figures). since the center wires stayed approximately the same distance from the pigtail conductor. As noted in Section 2.5, however, the reader should be aware that the calculations here assume that the majority of the coupling takes place along short space where the center conductor and pigtail run parallel, which may not be the case depending on the specific geometry of the grounding and cable configuration.

Table 3.5.1. Model Parameters for Substation Layout 5

Parameter	Value
Wire Conductivity	$5.96 \times 10^7 \frac{S}{m}$
Ground Conductivity	$0.015 \frac{S}{m}$
Ground ε_r	20
Cable insulation ε_r	3.18
Min # Center Conductors/cable	7
Cable shield termination in switchyard	Short
Cable shield termination in shack	Short
Pigtail Length	4 cm
Pigtail Radius	4 mm
Pigtail Distance from Conductor	4 cm-5 cm
Conductor radius	1.5 mm

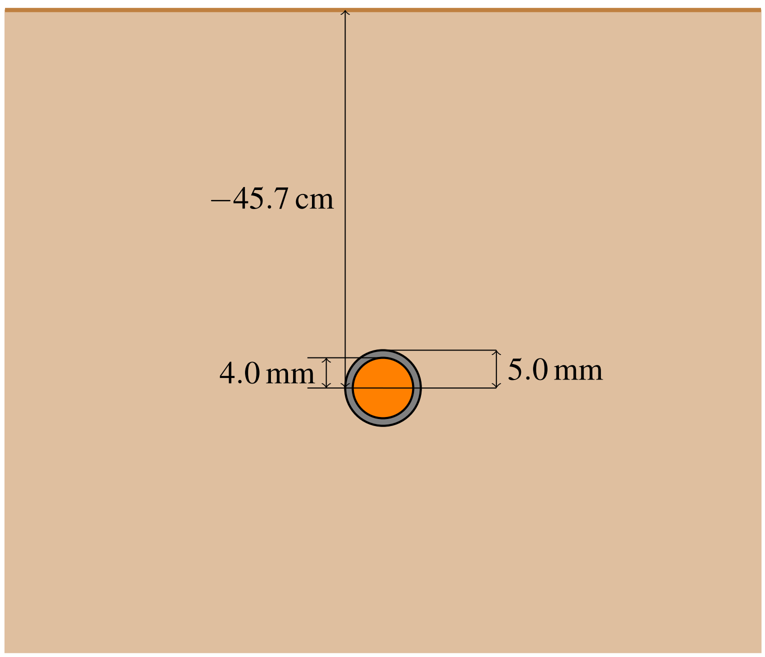


Figure 3.5.1. Buried Cable Coupling Setup for Layout 5. Note: Not to scale

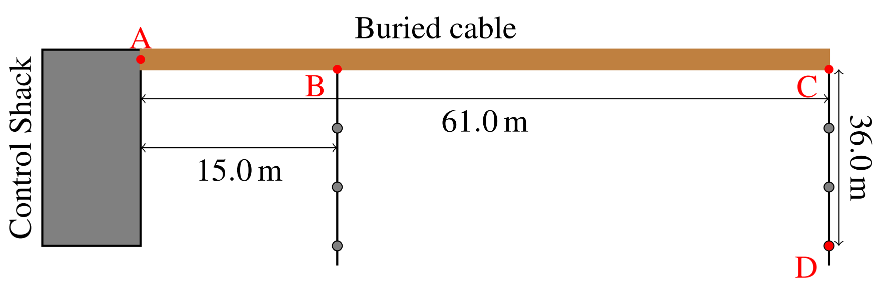


Figure 3.5.2. Substation diagram for Layout 5. Note: diagram not to scale; only shows min/max cable lengths lengths leaving control house simulated as well as max distance between trench and instrument as simulated.

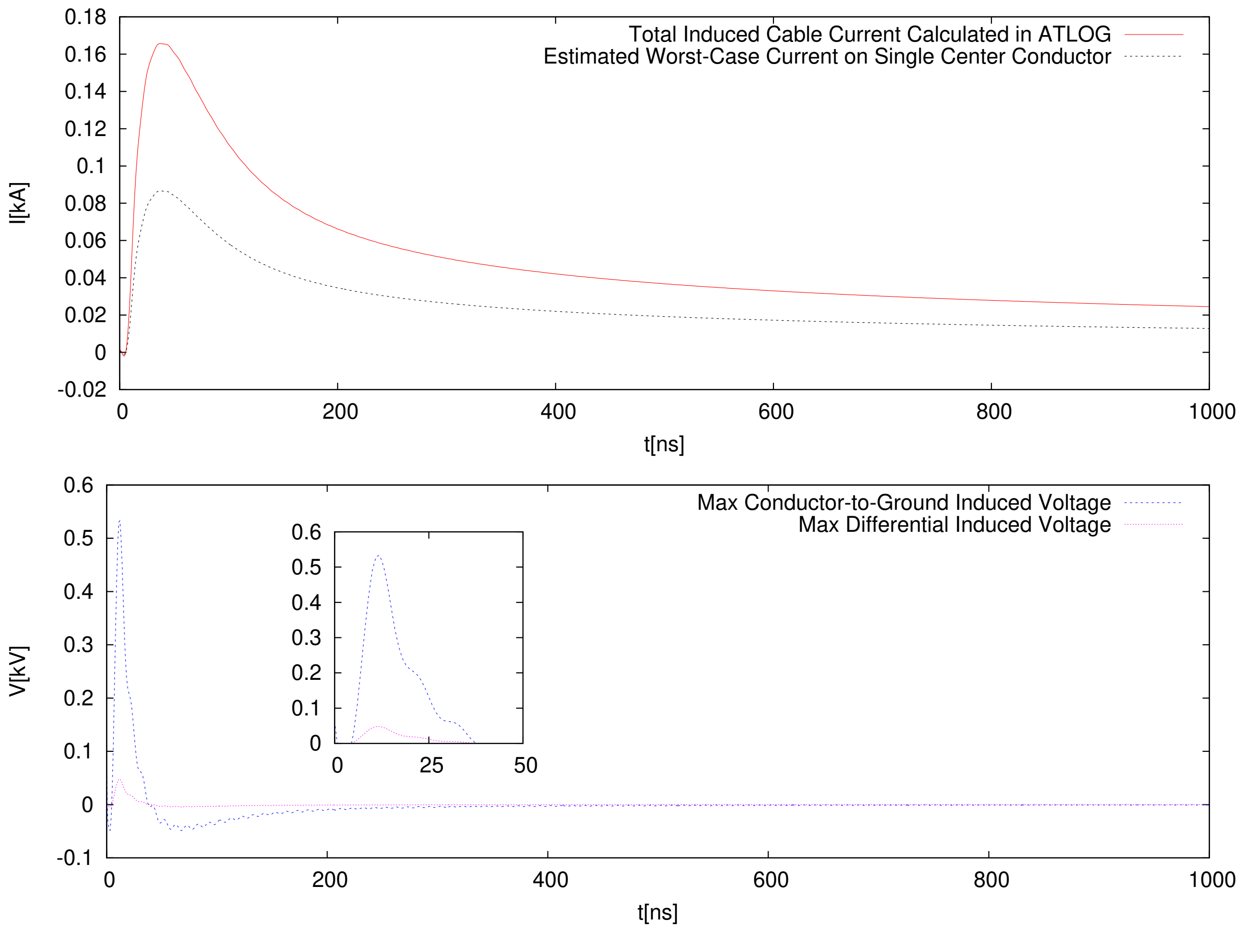


Figure 3.5.3. Currents and voltages on shortest cable leaving control house due to cable shielding and pigtail coupling for Layout 5. (Simulated measurements at point A due to coupling along length AB in Fig. 3.5.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2.

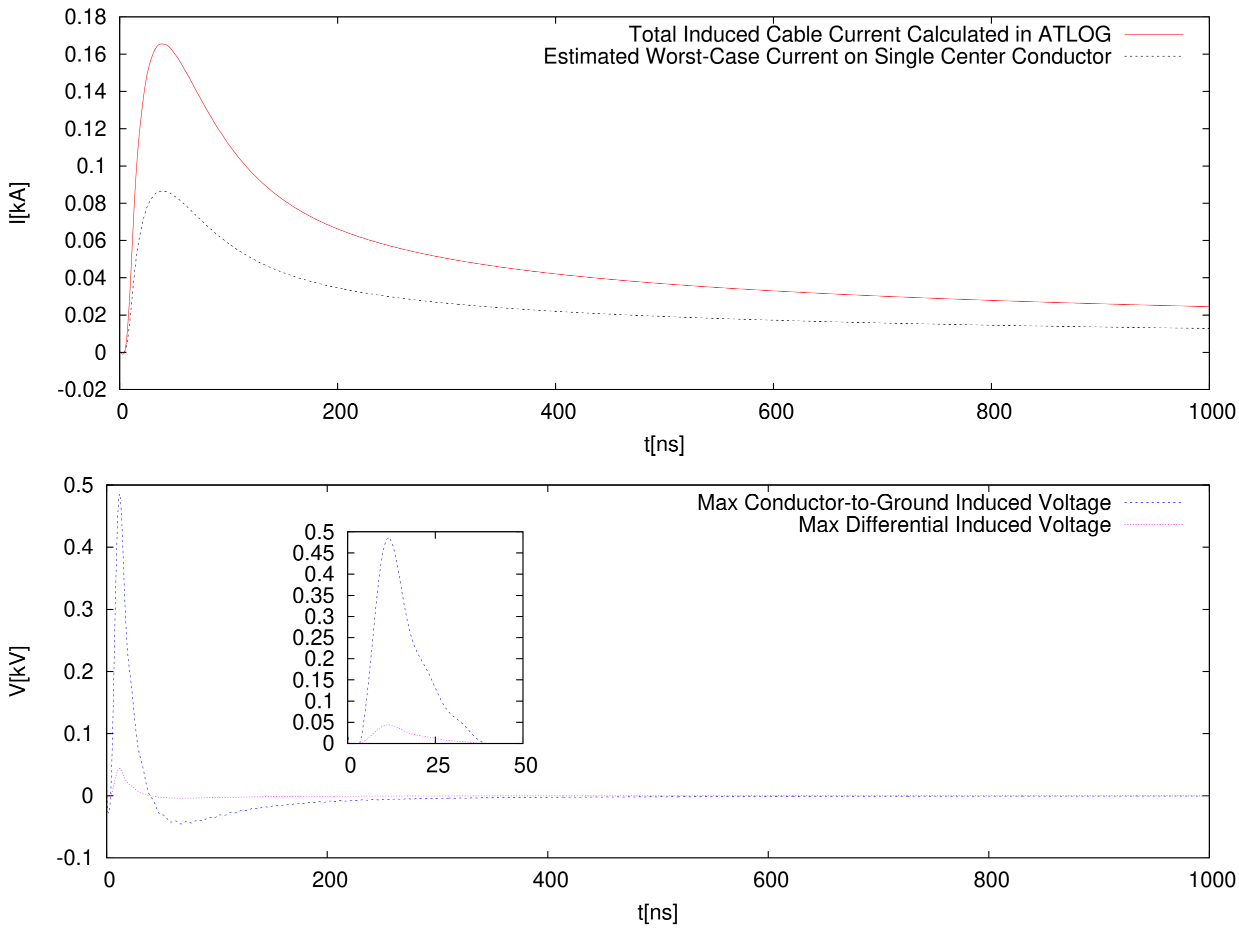


Figure 3.5.4. Currents and voltages on longest buried cable leaving control house due to cable shielding and pigtail coupling for Layout 5. (Simulated measurements at point A due to coupling along length AC in Fig. 3.5.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2.

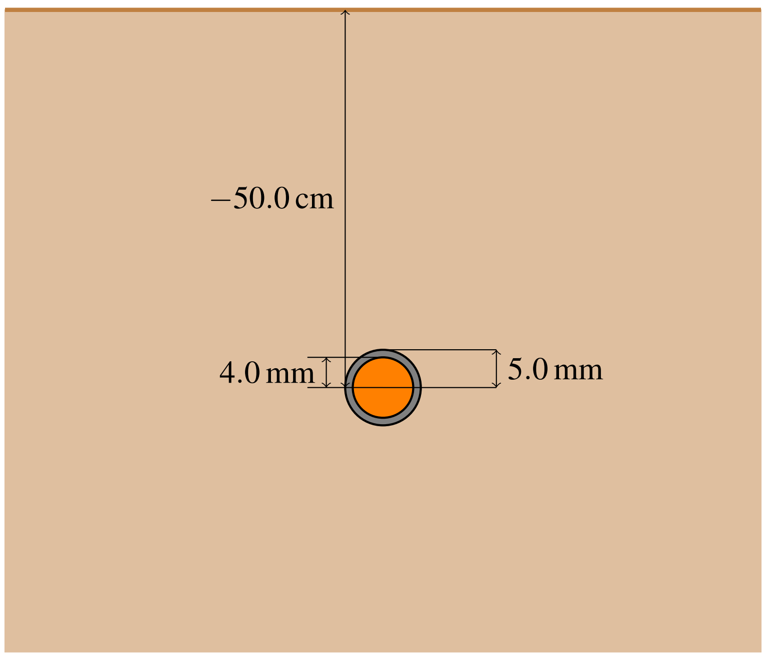


Figure 3.5.5. Cable between instrument and buried line to control house for Layout 5. Note: Not to scale

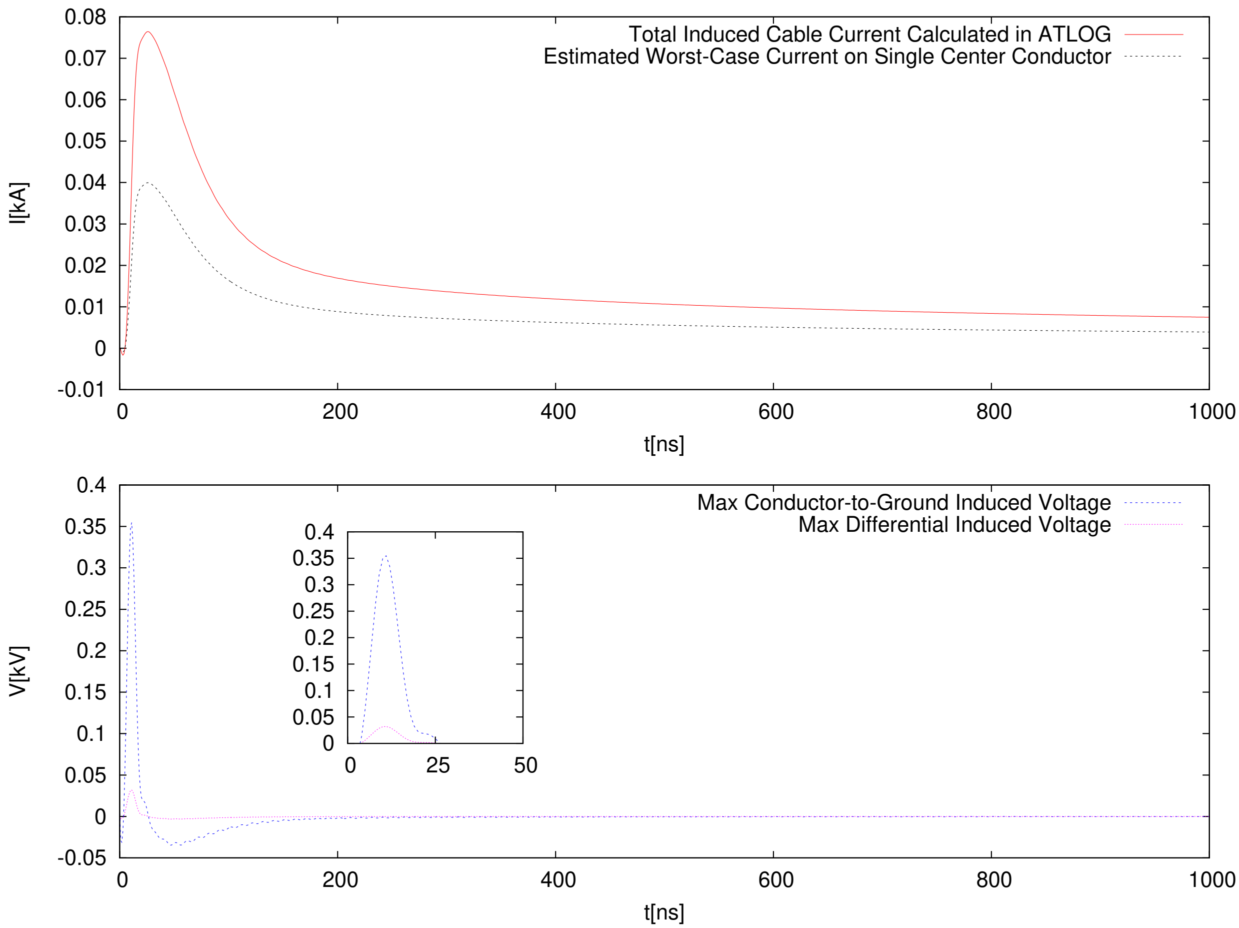


Figure 3.5.6. Currents and voltages on cable between instrument and buried line to control house due to cable shielding and pigtail coupling for Layout 5. (Simulated measurements at point C due to coupling along length CD in Fig. 3.5.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2.

3.6. Substation Layout 6

The sixth cable layout addressed here is modeled after Substation 2 of [8] in the southwestern U.S. (Note that the detailed layout given in [8] is reproduced in Fig. 2.3.2a.) The cables leave the control house in trenches of depth $\approx 0.5\,\text{m}$. As noted in [8], construction specifics are unavailable and a similar construction to that of Layout 4 (Substation 1 in [8]) is assumed. The cables are shielded with a braided mesh which is grounded via pigtail within the control shack, and ungrounded at the instrument in the control yard. The cable lengths modeled are diagrammed in Fig. 3.6.2. It is assumed that the induced current flows on the shield and so the cable shields are modeled as solid cylindrical conductors. The ATLOG model for the trench cables is shown in Fig. 3.6.1, and currents calculated for the shortest and longest cable runs (AB and AC in Fig. 3.6.2, currents calculated at A) are shown in Fig. 3.6.3 and Fig. 3.6.4, respectively, along with the estimated voltages induced on the center conductors in the control shack due to shield pigtail currents.

Cables are routed from the trench to the instruments themselves through buried PVC conduits. The ATLOG model for this is illustrated in Fig. 3.6.5. In this instance, a thicker PVC insulation around the cable is used in the simulation in order to approximate the effect of the PVC conduit, though this is expected to be minimal. The coupled currents are shown in Fig. 3.6.6.

Table 3.6.1 lists generic parameters and assumptions for this substation and the ATLOG models.

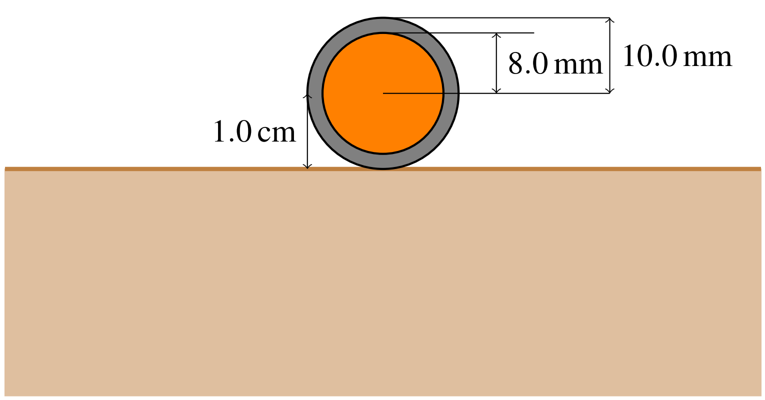


Figure 3.6.1. Trench Cable Coupling Setup for Layout 6. Note: Not to scale (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

Table 3.6.1. Model Parameters for Substation Layout 6

Parameter	Value
Wire Conductivity	$5.96 \times 10^7\ \frac{S}{m}$
Ground Conductivity	$0.015\ \frac{S}{m}$
Ground ε_r	20
Trench Cable insulation ε_r	3.18
Min # Center Conductors/cable	4
Cable shield termination in switchyard	Open
Cable shield termination in shack	Short
Pigtail Length	0.5 m
Pigtail Radius	2.6 mm
Pigtail Distance from Conductor	0.6 cm-15 cm
Conductor radius	2.6 mm

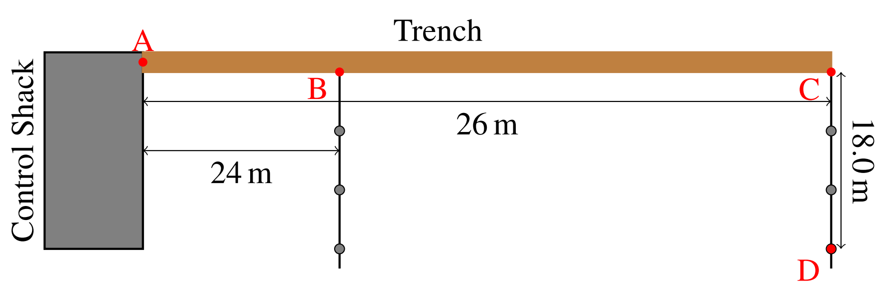


Figure 3.6.2. Substation diagram for Layout 6. Note: diagram not to scale; only shows min/max trench lengths simulated as well as max distance between trench and instrument as simulated. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

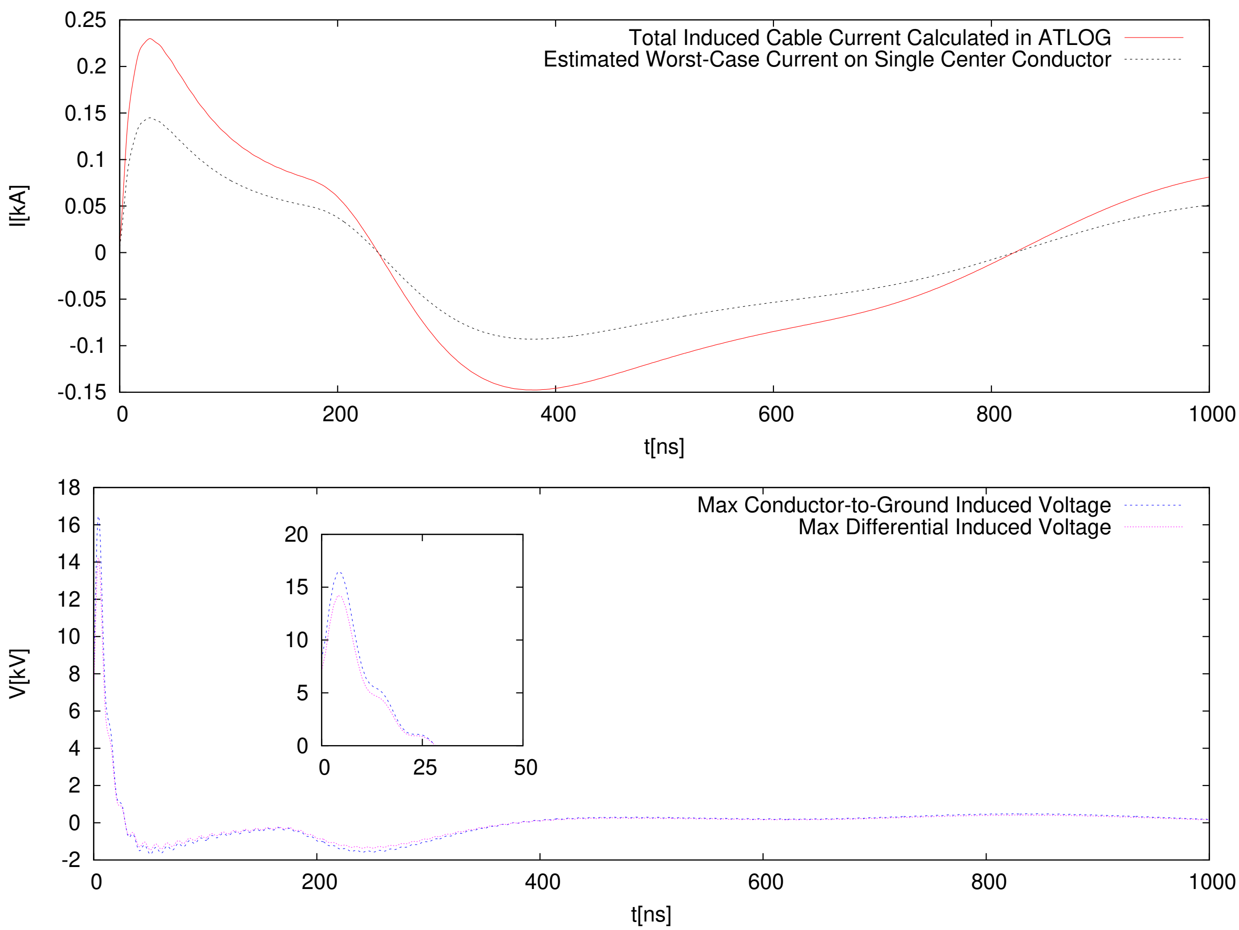


Figure 3.6.3. Currents and voltages on shortest trench cable due to cable shielding and pigtail coupling for Layout 6. (Simulated measurements at point A due to coupling along length AB in Fig. 3.6.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

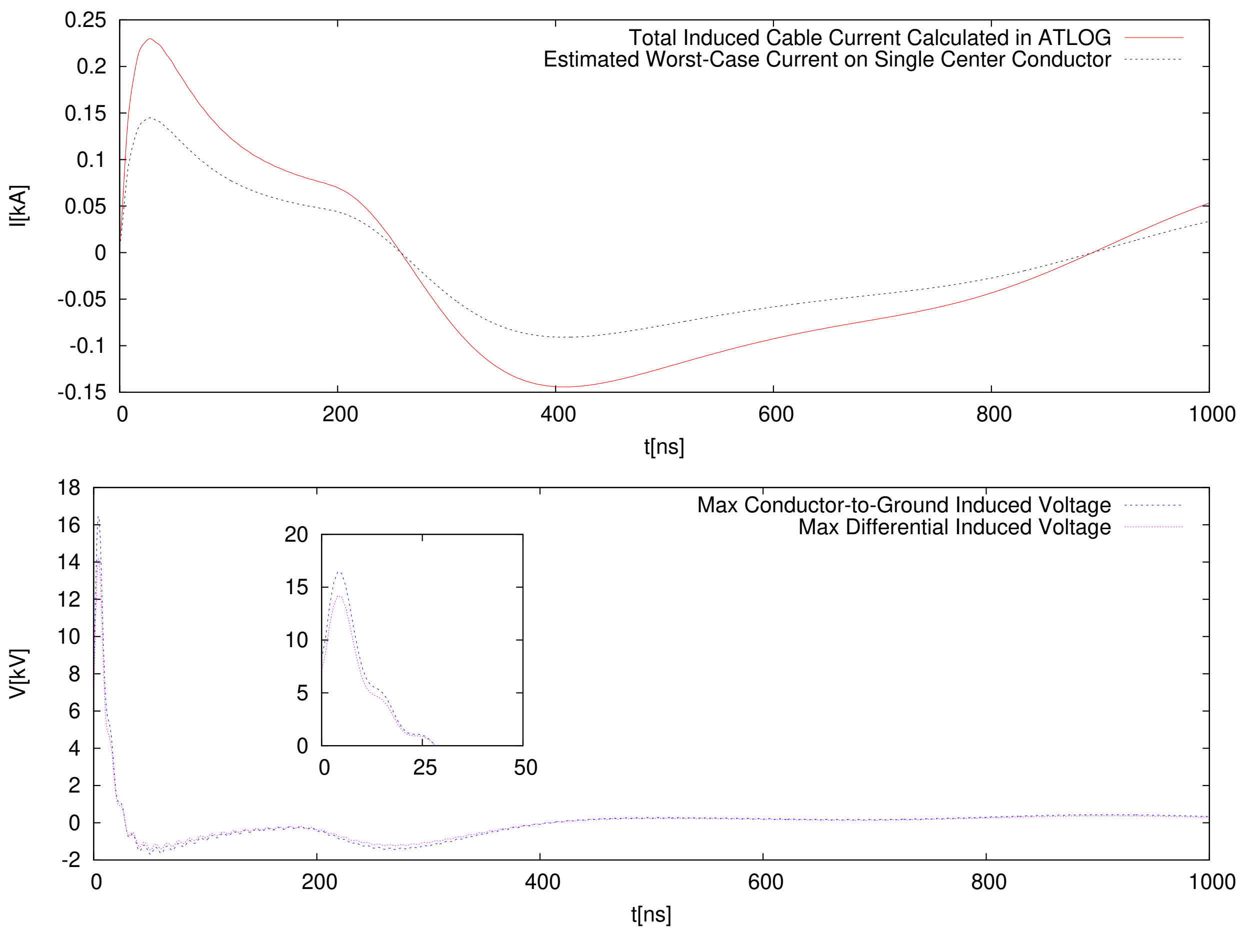


Figure 3.6.4. Currents and voltages on longest trench cable due to cable shielding and pigtail coupling for Layout 6. (Simulated measurements at point A due to coupling along length AC in Fig. 3.6.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

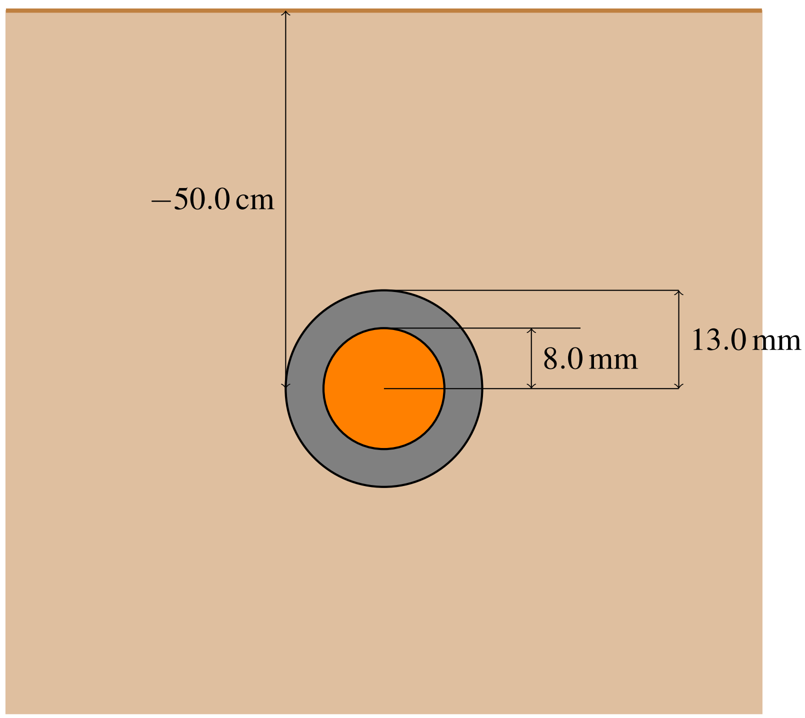


Figure 3.6.5. Cable between instrument and trench for Layout 6. Note: Not to scale

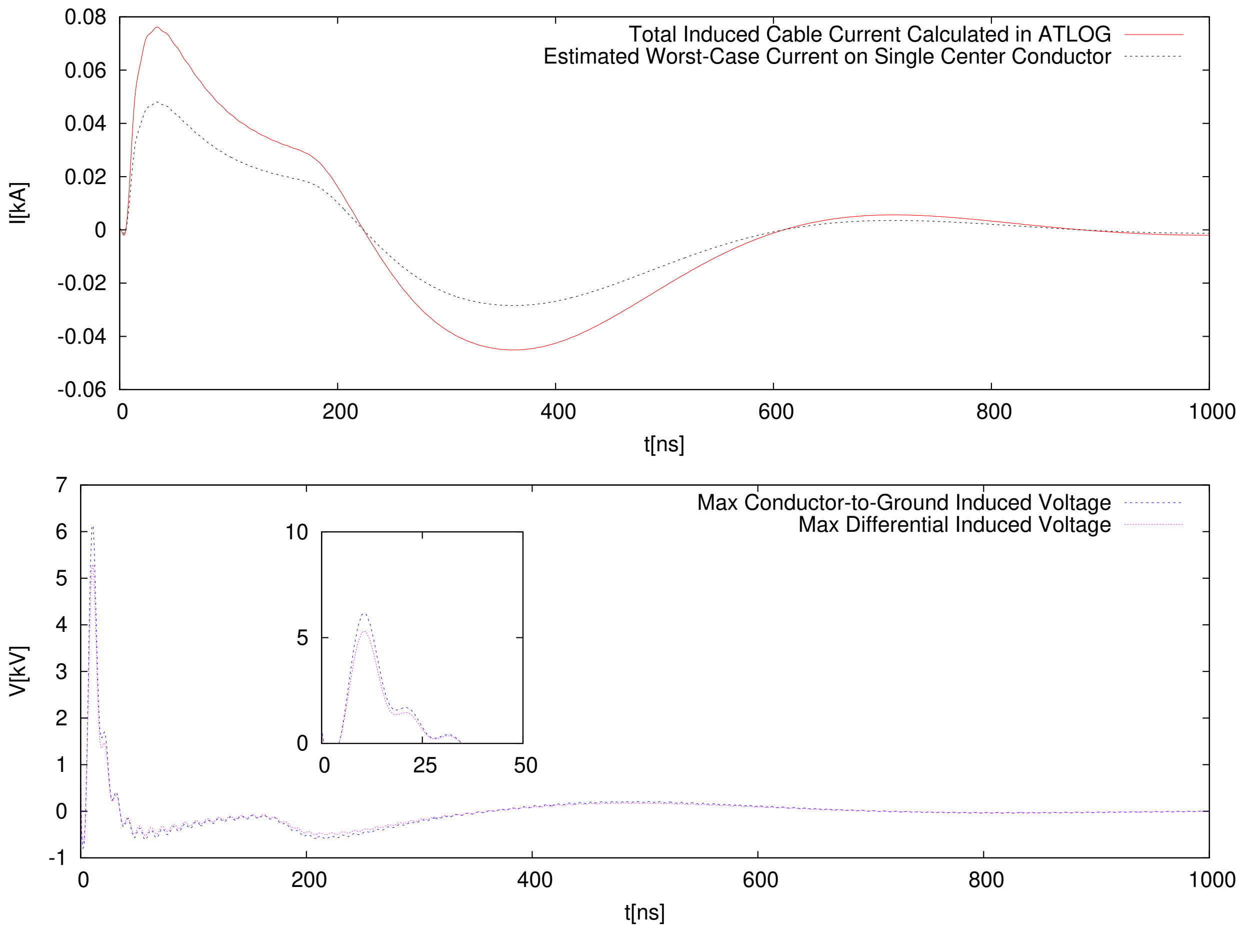


Figure 3.6.6. Currents and voltages on cable between instrument and trench due to cable shielding and pigtail coupling for Layout 6. (Simulated measurements at point C due to coupling along length CD in Fig. 3.6.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2.

3.7. Substation Layout 7

Cable Layout 7 is based on Substation 3 of [8] somewhere in the American Midwest. Cables leave the control shack in concrete trenches (≈ 0.3 m depth) that are not reinforced with rebar and are covered with panels made from concrete and fiberglass. The inner conductors of the cable bundles are shielded by an outer shield of stranded copper conductors like that found in Fig. 2.5.1. These shields are grounded via pigtails both at the instrument in the yard and in the control shack. Material parameters and other modeling assumptions are tabulated in Table 3.7.1.

The cable lengths used in the ATLOG models are diagrammed in Fig. 3.7.2. The simulation results at point A for coupling to lines AB and AC, respectively, are plotted in Fig. 3.7.3. and Fig. 3.7.4, the simplified ATLOG model for which is diagrammed in Fig. 3.7.1 (as previously the entrenched cable is modeled as lying on top of a flat ground). As shown in these figures, the rise of the current to a peak of approximately 0.23 kA would, if the entire current flowed on the pigtail in the control house, induce an open-circuit wire-to-ground voltage of approximately 8 kV.

Cables leave the trench in buried conduits approximately 0.5 m deep. The longest length of such a conduit (37.3 m) is modeled as shown in Fig. 3.7.5, and ATLOG is used to calculate the currents at the near end (C in Fig. 3.7.2), which is modeled as connected to ground through a 100 Ω load, while the far end (D in Fig. 3.7.2) is treated as shorted to ground. The resulting cable currents are plotted in Fig. 3.7.6, along with the voltages that these currents would induce on the center conductors by flowing on the pigtail in the control shack (though they will likely experience some attenuation before reaching that point). Note that although the peak current is only 0.1 kA, the induced voltage is still estimated at over 5 kV.

Table 3.7.1. Model Parameters for Substation Layout 7

Parameter	Value
Wire Conductivity	$5.96 \times 10^7\ \frac{S}{m}$
Ground Conductivity	$0.015\ \frac{S}{m}$
Ground ε_r	20
Trench Cable insulation ε_r	4.0
Min # Center Conductors/cable	4
Cable shield termination in switchyard	Short
Cable shield termination in shack	Short
Pigtail Length	0.25 m
Pigtail Radius	2.5 mm
Pigtail Distance from Conductor	0.6 cm-15 cm
Conductor radius	1.5 mm

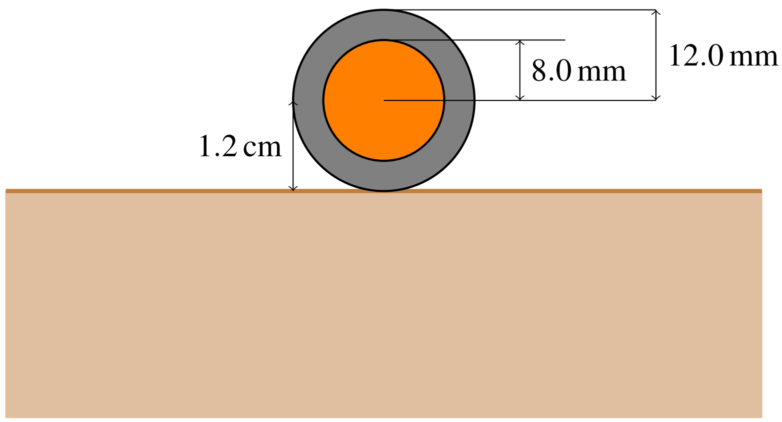


Figure 3.7.1. Trench Cable Coupling Setup for Layout 7. Note: Not to scale (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

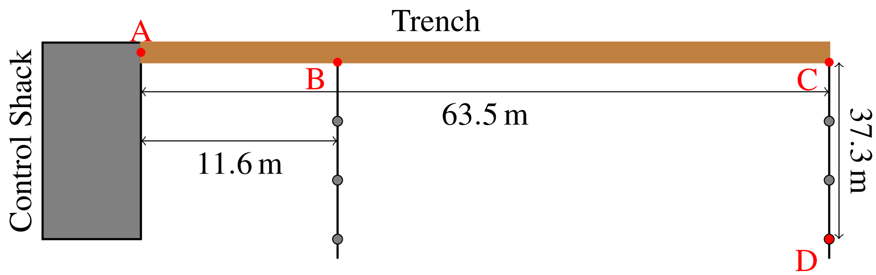


Figure 3.7.2. Substation diagram for Layout 7. Note: diagram not to scale; only shows min/max trench lengths simulated as well as max distance between trench and instrument as simulated. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

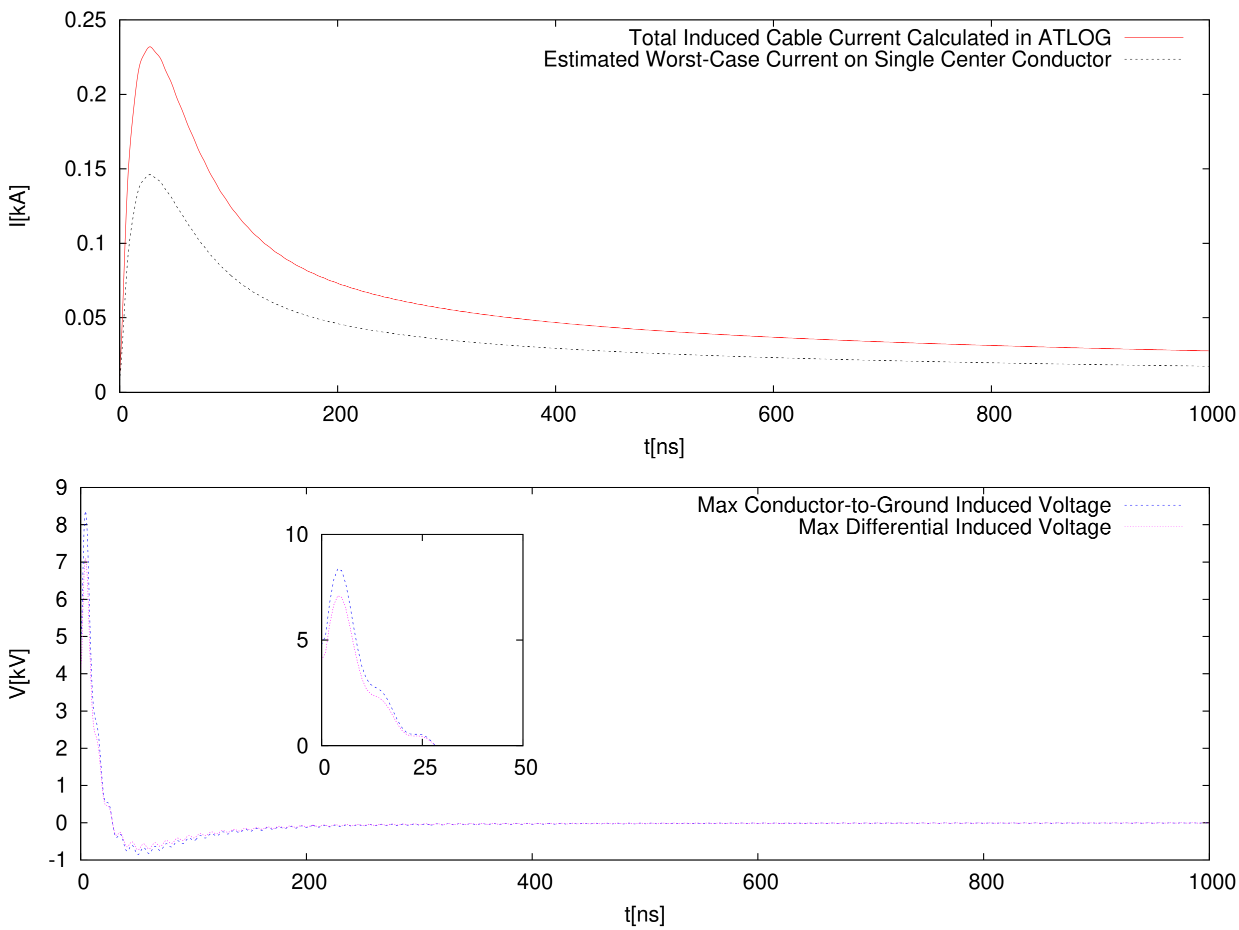


Figure 3.7.3. Currents and voltages on shortest trench cable due to cable shielding and pigtail coupling for Layout 7. (Simulated measurements at point A due to coupling along length AB in Fig. 3.7.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

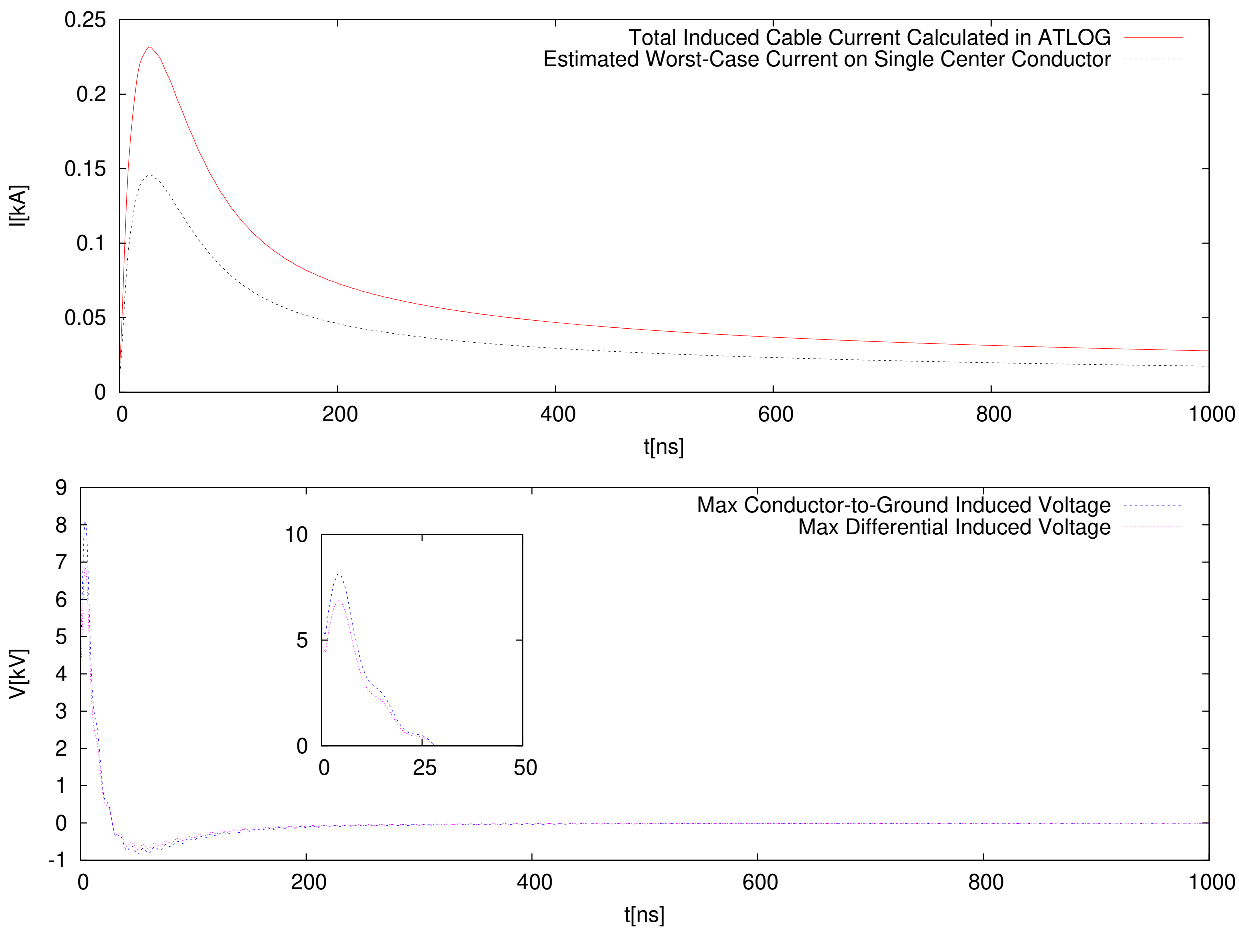


Figure 3.7.4. Currents and voltages on longest trench cable due to cable shielding and pigtail coupling for Layout 7. (Simulated measurements at point A due to coupling along length AC in Fig. 3.7.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2. (Trench cable is modeled as insulated solid conductor lying on top of flat ground.)

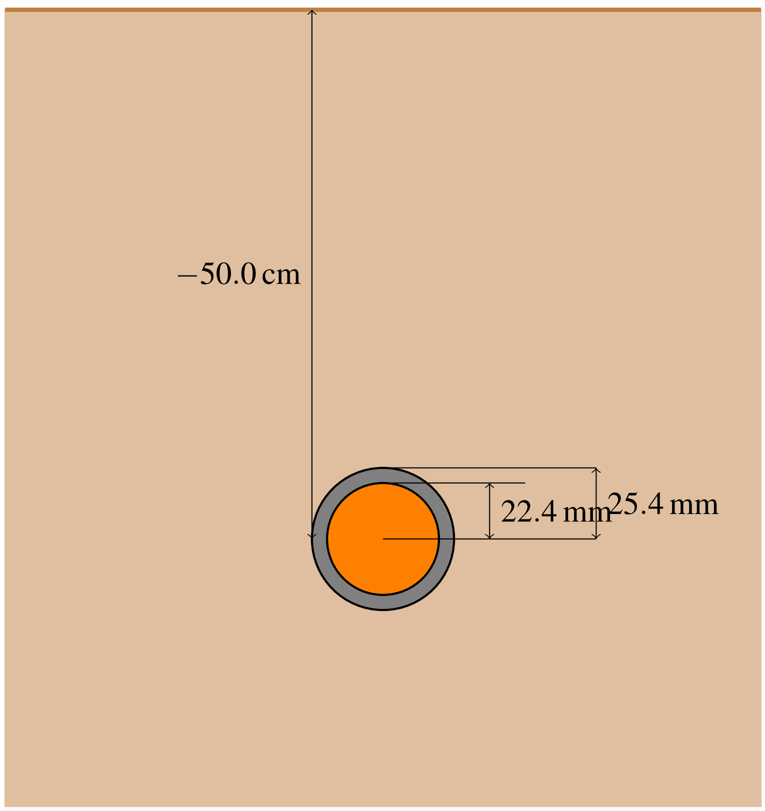


Figure 3.7.5. Cable between instrument and trench for Layout 7. Note: Not to scale

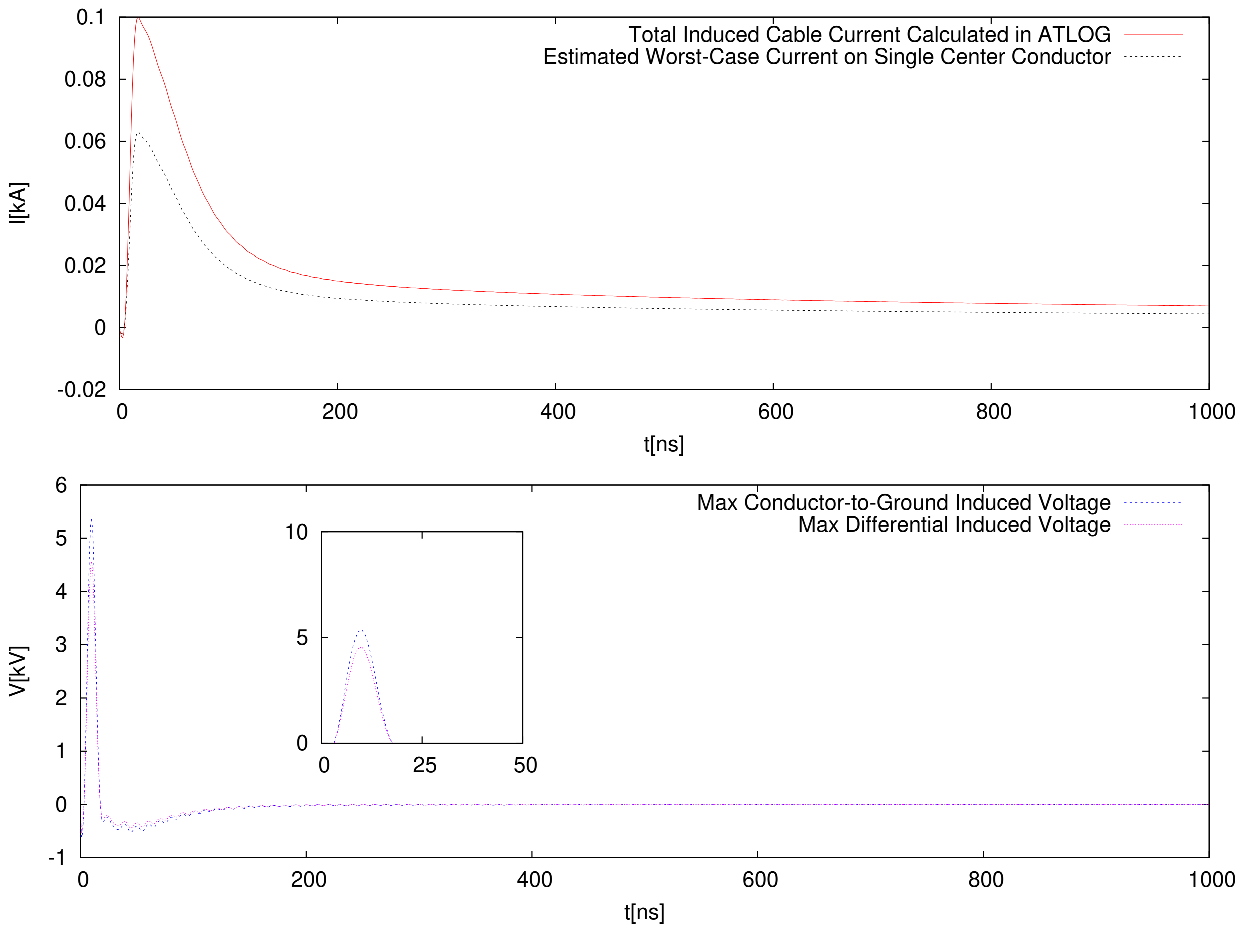


Figure 3.7.6. Currents and voltages on cable between instrument and trench due to cable shielding and pigtail coupling for Layout 7. (Simulated measurements at point C due to coupling along length CD in Fig. 3.7.2.) The estimated worst-case current on a single center conductor is also provided for reference and is calculated as the total induced cable current divided by the cube root of the minimum observed number of center conductors (see Section 2.5). "Max conductor-to-ground induced voltage" indicates voltage between point P and ground in Fig. 2.5.2. "Max differential induced voltage" indicates voltage between point P and point Q in Fig. 2.5.2.

4. DISCUSSION

Several general trends are noted in comparing the simulation data presented in Section 3.

First, the length of the transmission line does not strongly affect the amplitude of the induced current at the control shack. Most substations showed a peak induced current of around 0.15 kA-0.25 kA. While the length of the cable did not significantly affect this peak amplitude (due, ostensibly, to the propagation delay of the signal induced farther away on the line), it did affect the duration of the pulse. The results for Layout 4 illustrate this conspicuously; the reflection from the far end of the line (that is, the end in the control yard) reaches the shack more quickly causing a quicker drop in induced current. This effect is more clearly illustrated in the results for Layout 2, where the trench lengths, ranging from 4 to 12 meters, allow for more immediate interference with the reflected signal, **which does in fact lower the initial current peak**. The rapid decay of the signal in this case is also worth noting, and can also be seen in the instrument-to-trench runs of similar length.

Second, the behavior of the induced current is similar between a direct-buried line (as in Layouts 1, 3, and 5) and a cable lying on top of the ground (remaining layouts). Typical peak currents for unburied cables are around 0.23 kA, while those for buried cables are nearer 0.17 kA. This appears consistent with results obtained with ATLOG in [2, Figure 3], where a burial depth of 3 meters (more than six times the maximum depth seen here) only reduces the peak by a factor of $\approx 2/3$. This is due to the low ground conductivity at the substations studied here (and the consequently small amount of shielding that the ground provides). As seen in comparing [2, Figure 3] with [2, Figure 2], however, raising the ground conductivity by a factor of 10 significantly increases the shielding provided by the ground and dramatically reduces the peak induced current for the buried cable versus the cable on top of the ground. In view of these observations, the use of a wire-on-top-of-ground simulation to model a cable in a shallow trench appears justified.

Third, in those substations where cable shields are grounded in the control shack the induced voltage due to these grounding “pigtails” is significant. Moreover, as with the induced current, the length and positioning of the cable in the control yard do not have a strong influence on the voltage. Rather, the mutual inductance between the shield ground connection or pigtail and the center conductor connected to the instrument appears to be the primary factor. This suggests that the grounding of the shields within the shack itself is of a comparatively high importance in designing electrical substations for HEMP resilience. This is done by routing the wires and pigtails so as to minimize the loop enclosed, but in a complicated geometry consisting of several wires and grounding structures this is not a trivial problem. One solution would be to enclose the metering devices in grounded metal cabinets and ground the shield around the center conductors at the aperture where the cable enters the cabinet. The Faraday cage that this would create around the center conductors between the ground and the point where they exit the shield could substantially reduce the coupling (see [1]).

Fourth, while significant currents can be induced by coupling to the cable running between the cable trench and the instrument, these are highly oscillatory and decay rapidly in time, but further work is needed to assess the spatial decay and consequent magnitude of the signal when it reaches the control house. The coupling to the line between the instrument and the trench may also be of importance if effects on the instrument itself are being examined, but this is outside the scope of this report. It is also important to bear in mind that the coupling to vertical lines in the case of grazing HEMP incidence with the incident electric field normal to the ground will be significant and may even exceed the effects computed here for normal incidence to horizontal cables, but this is a subject for further work.

With reference to the fourth point, recall that the ATLOG software used for these simulations does not allow for simultaneous coupling to multiple transmission line segments, as noted in Section 2.3. Further work will therefore be required not only to quantify the decay of the instrument-to-trench signal as it travels to the control house, but also to determine in detail the combined effects of two (or more) segments when the incident field is partially aligned with both, that is, when the electric field is at right angles to neither cable.

5. CONCLUSION

In this report simplified transmission-line models of the substations described in [8] have been described, and simulations of HEMP effects on these models have been collected for comparison and analysis. While the substantial simplifications required for modeling purposes leave open questions about the precise effects to be expected in physical substation layouts, general trends may nevertheless be discerned.

While the induced currents calculated and plotted here for unshielded instrument cables may give some insight into HEMP effects at device terminals with a low impedance to ground, they do not accurately reflect the response of general devices. This would require a more sophisticated modeling of device impedance across the appropriate frequency range, which is beyond the scope of the present report.

With regard to the pigtail-induced voltages at the terminations of shielded instrument cables it was noted that cable length and situation appear to have little influence on the peak magnitude of the coupled voltage. The pigtail routing relative to the center conductors, however, may have rather a significant influence, and should be taken into account in wiring substations where HEMP effects are of concern.

The effort documented here has highlighted several opportunities for future modeling work. These include the detailed analysis of simultaneous HEMP coupling to several horizontal and vertical cable segments with different heights or burial depths and directions. The development of more detailed circuit models for the measurement instruments as well as the metering and relay devices connected to the cable would also make possible a more precise prediction of HEMP effects on a given substation. The effects of metal grounding grids buried under substations could also be examined.

APPENDIX A. Cable Shielding Effectiveness

As mentioned in Section 2.5, control cable shielding comes in different types. While the dense copper meshing used at some substations with high optical coverage may be expected to provide effective shielding across the frequency spectrum of the E1 pulse, this is not so obvious for the coarse stranded shield found at some substations (see Fig. 2.5.1).

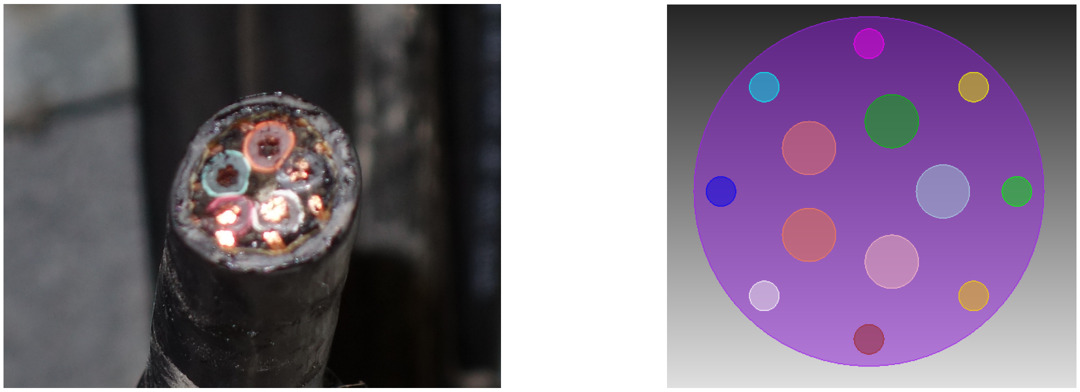
In order to gauge the effectiveness of the stranded shield, a simple test was run using Sandia's method-of-moments software EIGER to analyze a 2D cross section of such a cable. The cross section geometry model shown in Fig. A.0.1 was generated using the meshing software CUBIT, and consists of a PVC insulation (large violet circle) in which are 5 center conductors of radius 1.8 mm surrounded by 8 shield strands, each of radius 1 mm.

The analysis performed by EIGER treats the geometry in Fig. A.0.1 as the cross section of an infinite cylinder; the results below thus reflect the currents that should be expected on the wires away from the ends of a very long cable. The wires are modeled as solid copper ($\sigma = 5.96 \times 10^7\ \frac{\mathrm{S}}{\mathrm{m}}$) and the PVC is given a relative permittivity of 3.18. The wire is subjected to an incident sinusoidal plane wave normally incident to the wire axis and having an electric field with amplitude $1\ \frac{\mathrm{V}}{\mathrm{m}}$ oriented parallel to the wire axis. The simulation is performed at frequencies across the spectrum of the incident EMP environment, specifically, at 20 linearly-spaced frequency points beginning at 100 kHz and ending at 100 MHz.

The total current induced on the shield as well as on the center conductors (collectively as well as individually) is shown in Fig. A.0.2. Three things are worth noting in the plot. First, the shield carries approximately 10 times the total current induced on the center conductors taken together, or about 90 % of the total induced current. Second, the current distribution does not vary noticeably across the frequency range. Finally, note that the current induced is approximately the same on each of the center conductors.

As remarked in Section 2.5 a bundled cable is represented in ATLOG as a single cylindrical conductor. In order to gauge the suitability of this model the same analysis as above is run replacing all 13 shield and center conductors with a single copper conductor whose circumference passes through the centers of all 8 shielding wires in Fig. A.0.1. The total current induced on this conductor is shown in Fig. A.0.2 for comparison with the other induced currents as well as in Fig. A.0.3, where it is compared to the total current induced on all 13 conductors in the sparsely shielded bundle. As is evident in the graph, the total induced current does not differ noticeably between the two models.

While further work is needed for a more comprehensive knowledge of shielding effectiveness, the results here suggest that the sparse strands provide some shielding to the inner conductors. One point worth noting, however, is that this analysis assumes an infinite, uniform cable. In the first place, it should be noted that for a physical, finite cable with the shield grounded at both ends, and



(a) Sample cable from Layout 7.   (b) CUBIT geometry model.

Figure A.0.1. Sparsely shielded cable cross section.

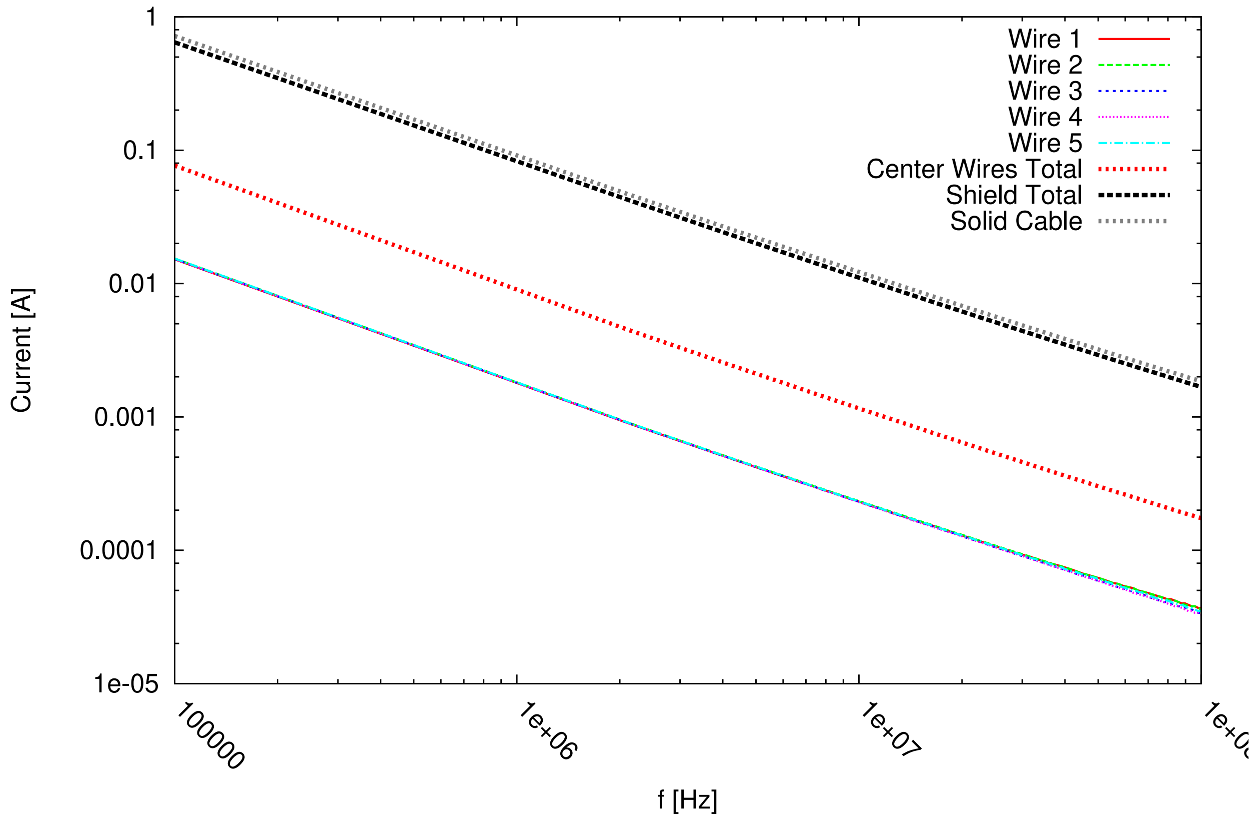


Figure A.0.2. Current coupling calculations for cable model.

with the center conductors terminated in low impedance loads, the results shown in Fig. A.0.2 will not be accurate at lower frequencies, where more current will tend to flow on the center conductors. If one or both terminations of the shield are ungrounded, this can also substantially reduce the effectiveness of the shield. Moreover, even in this idealized setup a significant current is still induced on the inner conductors collectively. In reality, asymmetries in the cable may cause the current to be unevenly divided among the inner conductors. **These considerations**

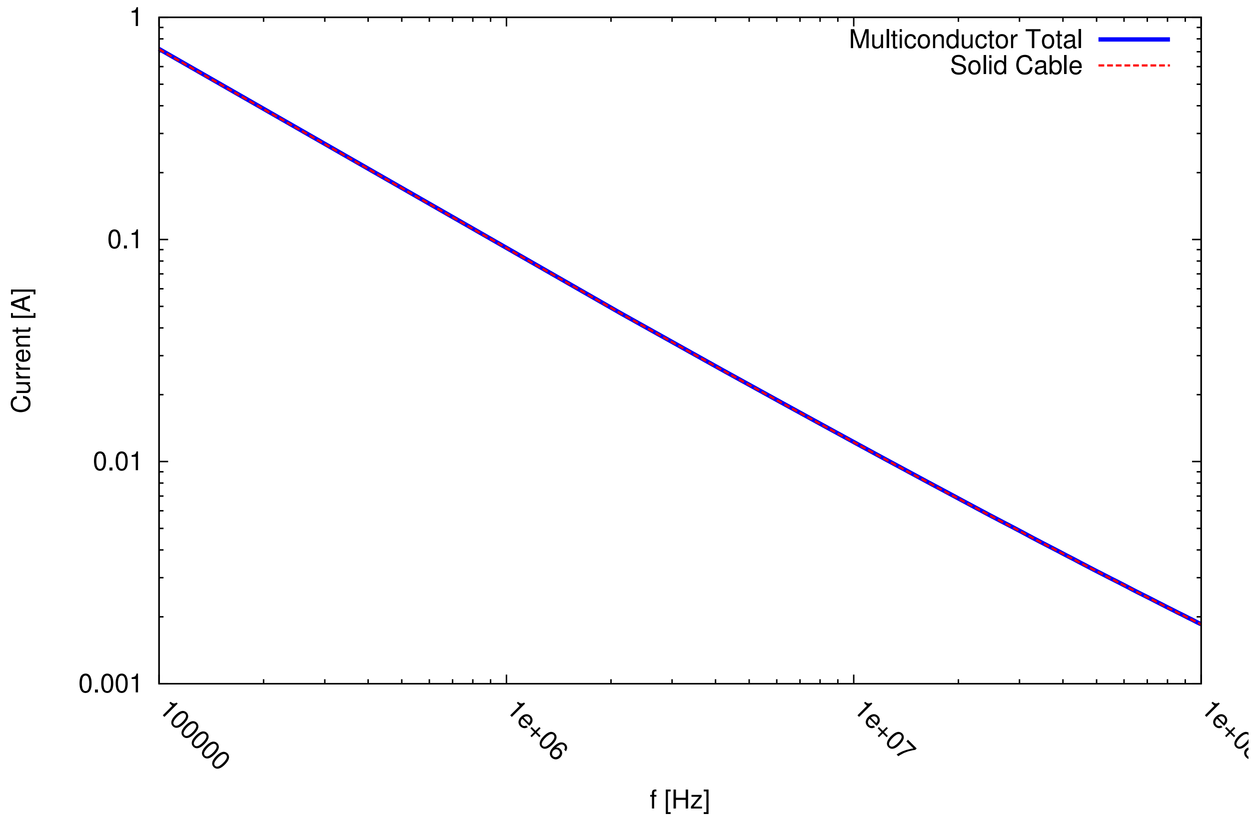


Figure A.0.3. Current on single solid cable compared to total current induced on all wires (shield and center) in sparsely shielded cable.

indicate that a large current may still be induced on one or multiple center conductors and that the cables employing this sparse, stranded shielding should not be considered "well-shielded" in the context of this report.

APPENDIX B. Coupling to Vertical Cable Sections

The simulations performed in this paper address coupling due to HEMP waves normally incident to the ground, since this creates maximum coupling on the horizontal cables in the substation control yard. As was seen in Section 3, however, some substations also have vertical segments of cable between the buried line or trench and an elevated line traveling to the instruments (as in Fig. 1.0.2). On such a line maximum coupling will be achieved when the wave is at grazing incidence, that is, when the angle θ_0 in Fig. 2.2.1 is near 0°. In such a situation a significant current can be induced on the vertical conductor, particularly since the incident field is augmented by a reflection from the conducted ground. As mentioned in Section 2.3, this cannot be simulated in the ATLOG software used here, and so an analytic approximation of a vertical wire connected to a ground plane is used, with a capacitative load at the top to account for the elevated horizontal cable. A PEC ground plane is used to estimate a worst-case reflection.

The capacitance per unit length between the elevated cable of radius a, height h, length ℓ (see Fig. B.0.1) and the ground plane is approximated as

$$C_\ell = \frac{2\pi\varepsilon_0}{\operatorname{acosh}(h/a)} \tag{B.1}$$

and a terminating impedance for the far end of the elevated cable calculated as in [11]

$$C_t \approx 2hC_\ell \frac{1+\frac{4}{\Omega}\left(1-\ln(2)\right)}{\Omega} \tag{B.2}$$

with the fatness parameter Ω calculated as

$$\Omega = 2\ln\left(\frac{2h}{a}\right) \tag{B.3}$$

giving the total capacitance

$$C = \ell C_\ell + C_t. \tag{B.4}$$

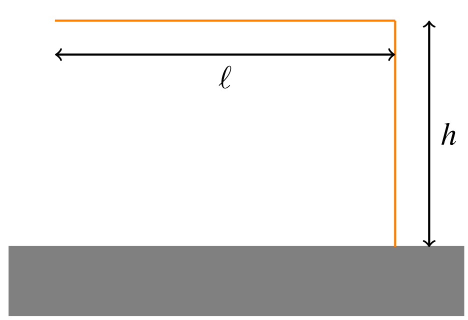


Figure B.0.1. Elevated cable dimensions.

The open-circuit voltage between the ground and the top of the cable is given by

$$V_{oc} \approx -hE_z = -h(E_z^{\text{inc}} + E_z^{\text{ref}}) \tag{B.5}$$

where E_z^{inc} and $E_z^{\text{ref}})$ are the incident and reflected portions of the electric field. At grazing incidence over a PEC ground plane this becomes

$$V_{oc} = -2hE_z^{\text{inc}}. \tag{B.6}$$

The current induced on the wire is then estimated as

$$I = C\frac{d}{dt}V_{oc} = C \cdot 2h\frac{d}{dt}E_z^{\text{inc}}. \tag{B.7}$$

Using the IEC-61000-2-9 waveform (see Section 2.4) this becomes

$$I = C \cdot 2hKE_0(\alpha e^{-\alpha t} - \beta e^{-\beta t}) \tag{B.8}$$

for $t > 0$.

An example plot of the resulting current is plotted in Fig. B.0.2 for a cable of radius $a = 0.5\,\text{cm}$, height $h = 2\,\text{m}$, and length $\ell = 3\,\text{m}$, which has, using the formulas above, a total capacitance $C = 35.8\,\text{pF}$. Although this low frequency circuit model may not be very accurate at the very early time, it does indicate that these induced currents can be substantial.

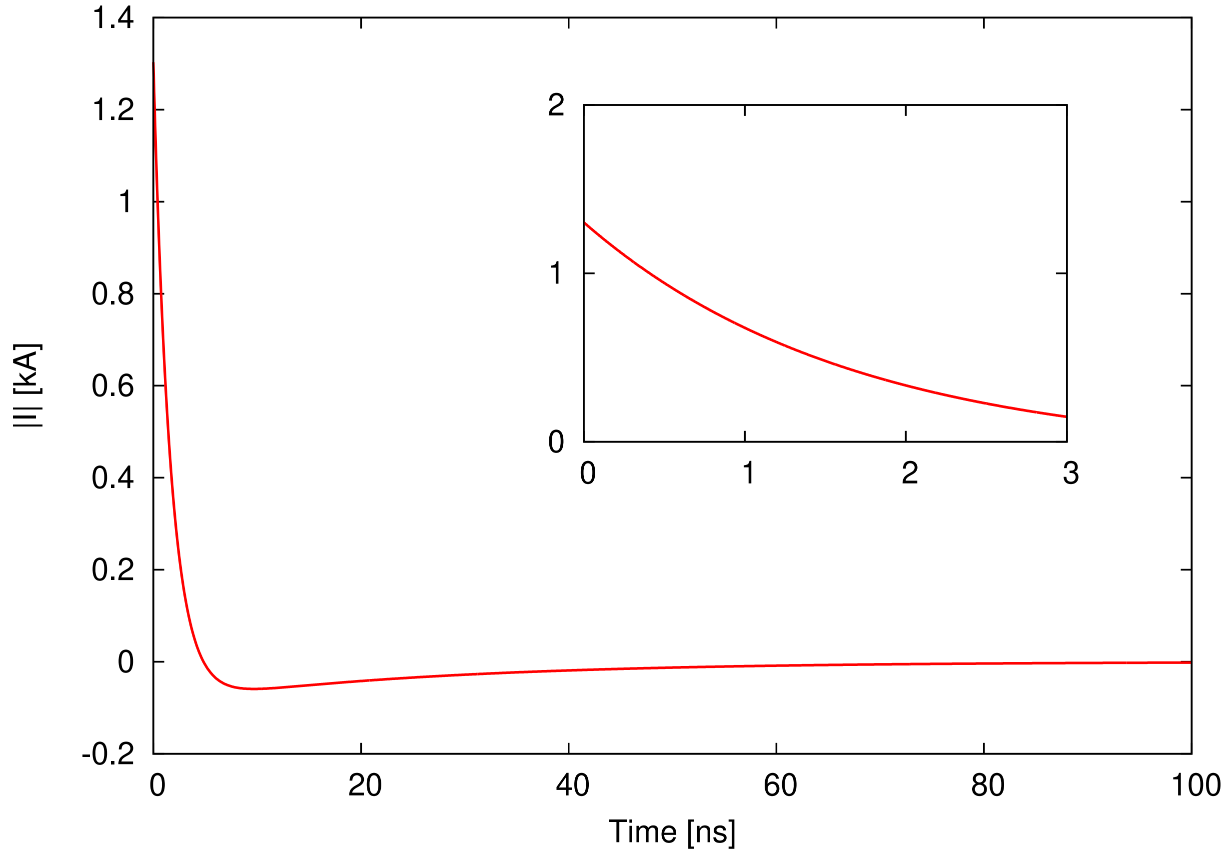


Figure B.0.2. Estimated current induced on example vertical cable by HEMP E1 field at grazing incidence.

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