Docket No. ______
Exh. TDI-WHB-4

Electrical Engineering & Computer Science Practice

Exponent®

Overland Magnetic Field Report for the New England Clean Power Link Project

Overland Magnetic Field Report for the New England Clean Power Link Project

Prepared for

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December 2, 2014

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Executive Summary

Champlain VT, LLC, d/b/a TDI New England is proposing the New England Clean Power Link project (NECPL or Project). The NECPL is a high voltage direct current (DC) electric transmission line that will provide electricity generated by renewable energy sources in Canada to the New England electric grid. The line will run from the Canadian border at Alburgh, Vermont, along underwater and underground routes to Ludlow, Vermont.

The transmission line will be comprised of two approximately five-inch cables—one positively charged and the other negatively charged—and will be solid-state dielectric and thus contain no fluids or gases. The nominal operating voltage of the cables is ±320 kilovolts, and the system will be capable of delivering 1,000 megawatts of electricity.

This report summarizes Exponent's calculations of the change in background static geomagnetic field produced by the DC magnetic field from the DC cables installed along the overland portion of the route and calculations of the post-construction AC magnetic field over a short AC interconnection. Since the grounded metallic sheathing around the cable and the earth itself shield the environment from the electric field, it was unnecessary to model electric fields. In addition, any electric field induced by movement of persons in the static field of the earth and cables at levels of microvolts per meter is too weak to be of interest.

Models of the overland installation of the DC cables were developed that include variations to account for cable placement, configuration, conduit material, and current polarity. All calculations of the DC magnetic field account for the joint contributions from the transmission line and the earth to obtain the total DC magnetic field that would be measured in its vicinity.

The overland portion of the line will be constructed in underground trenches, modeled in four separate modeling scenarios and an underground DC duct bank, modeled in two separate modeling scenarios. These scenarios represent the range of DC magnetic field level changes associated with the proposed Project. For very short distances the line also will be contained within steel conduits constructed in above ground attachments crossing a bridge or culvert (two configurations, approximately 150 feet), and in an alternating current (AC) duct bank (one configuration, approximately 3,000 feet within public roads). These modeling scenarios are discussed in the Appendices to this report.

The change in the ambient geomagnetic field level will be limited largely to the area immediately surrounding the NECPL cables. The calculated DC magnetic field deviations fall off rapidly with distance. At 25 feet to either side of the circuit centerline the maximum deviation from the ambient geomagnetic field will be less than 18% (the trench horizontal directional drilling configuration). For the remaining trench configurations (25 feet to either side of the cables) the change from ambient conditions will be less than 10%. In the duct bank configurations at a distance of 25 feet to either side of the circuit centerline, the maximum deviation from the ambient geomagnetic field will be less than 5%.

The highest calculated DC magnetic field level anywhere along the overland portion of the route (calculated at 1 meter above ground, directly over the NECPL cables) is approximately 1,660 mG, less than 0.04% of the general 4,000,000 mG public exposure limit for DC magnetic field levels recommended by the International Commission for Non-ionizing Radiation Protection (ICNIRP) and is below the applicable 10,000 mG medical device standard for exposure to DC magnetic fields. The highest level magnetic field above the AC interconnection is less than 3% of the ICNIRP general public exposure limit for 60-Hz AC magnetic fields and below applicable medical device standard for exposure to AC magnetic fields.

Introduction

Champlain VT, LLC, d/b/a TDI New England (TDI-NE), is proposing to install and operate the New England Clean Power Link project (NECPL or Project). The NECPL is a high voltage direct current (DC) electric transmission line[1] that will provide electricity generated by renewable energy sources in Canada to the New England electric grid. The line will run from the Canadian border at Alburgh, Vermont, along underwater and underground routes to Ludlow, Vermont. The transmission line will be comprised of two approximately five-inch diameter cables—one positively charged and the other negatively charged—and will be solid-state dielectric and thus contain no fluids or gases. The nominal operating voltage of each cable on the line will be ±320 kilovolts (kV), and the system will be capable of delivering 1,000 megawatts (MW) of electricity.

The overland portion of the transmission line, approximately 56 miles in length, will be buried approximately 4 feet underground within existing public (state and town) road rights-of-way. The only potential areas where the line cannot be buried are at two locations in Ludlow, Vermont, where the line will be attached to a bridge or on a headwall.

In Ludlow, the transmission line will terminate at a converter station that will convert the electrical power from DC to alternating current (AC).[2] An underground AC interconnection will connect the converter station to the existing 345 kV Coolidge Substation in Cavendish, Vermont, 0.3 miles to the south that is owned and operated by the Vermont Electric Power Company. An assessment of this AC interconnection is provided in Appendix B.

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1 Although electricity in the United States is transported primarily by AC transmission lines, DC transmission lines have been in operation in North America for over 40 years. These transmission lines operate at voltages of ±250 kV to ±500 kV. The highest voltage overhead DC transmission lines outside North America operate at ±800 kV.

2 When considering the electrical environment of a transmission line, it is important to recognize there are differences between AC and DC transmission. Since they transmit electricity at different frequencies (~0 Hertz for DC transmission and 60 Hertz for AC transmission), the magnetic fields produced interact with conductive objects, including human bodies, quite differently. The most important difference is that DC magnetic fields do not induce or couple currents and voltages in conductive objects, an effect that may occur from exposure to AC fields. Known safety hazards of work around energized transmission lines can be mitigated through adherence to the National Electric Safety Code.

DC magnetic fields[3] are produced by the flow of electric currents. The earth produces a ubiquitous natural background geomagnetic field that originates from the electrical currents in the earth's molten core and crustal sources. The geomagnetic field varies with latitude; it is highest at the magnetic poles and lowest at the equator (~700 and ~300 milligauss [mG], respectively). Man-made DC magnetic fields result from a number of sources: battery-powered appliances and toys, magnetic resonance imaging machines, electrified railways, and DC transmission lines, to name a few. Magnetic fields are calculated as magnetic flux density measured in units of Tesla or microtesla (μT) according to the International System of Units, or more commonly in units of gauss (G) or mG, where 1 μT = 10 mG. In this report, magnetic fields are reported in units of mG or G, as is most common in North America. Since magnetic fields are vectors characterized by magnitude and direction, magnetic fields from a DC transmission line add to or subtract from the earth's geomagnetic field; the combined magnetic field level is dependent on the orientation of the transmission line with respect to the earth's geomagnetic field. Unlike electric fields, magnetic fields are not easily shielded or attenuated by most conducting objects.

The main body of this report summarizes the methods used for calculations of DC magnetic fields and results for the DC trench and DC duct bank configurations (described in more detail below) since these configurations comprise approximately 99% of the overland route. The analyses of the modeling, methodology, and results for the bridge and headwall attachments are presented in Appendix A. The methodology modeling and results for the 60-Hz magnetic fields associated with the AC underground interconnection are presented in Appendix B.

[3] Electric and magnetic fields at 0 Hertz are also referred to as static fields. Electric and magnetic fields associated with the operation of a DC transmission line are referred to in this report as DC electric and magnetic fields. When produced in nature, these same phenomena are typically referred to as static electric and magnetic fields. While the terminology is different the phenomena are the same.

DC Magnetic Field Assessment Criteria

Several scientific and governmental agencies have established guidelines for exposure to DC magnetic fields, including the International Committee on Electromagnetic Safety, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), the Environmental Protection Agency, and the Food and Drug Administration. The most relevant and current exposure guideline for this project is the ICNIRP guideline that recommends that the general public not be exposed to static magnetic fields above 4,000,000 mG.[4] Higher exposure limits are recommended for workers in occupational environments. These limits are ceiling values; they apply to both short- and long-term exposure.

In addition, for persons with implantable medical devices, the limit for exposure to static magnetic fields is determined by other standards such as Association for the Advancement of Medical Instrumentation's PC69:2007 Standard, which specifies that no changes in the function of the pacemaker or the implantable cardioverter defibrillator should occur up to 1 millitesla (i.e., 10,000 mG). Up to a static magnetic flux density of 50 millitesla (i.e., 500,000 mG), a pacemaker or implantable cardioverter defibrillator should not remain functionally affected after discontinuation of the exposure.

[4] International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines on limits of exposure to static magnetic fields. Health Phys 96:504-514, 2009.

Methods

Over different portions of the route, the DC transmission line will be constructed in various configurations as shown in Table 1. A total of six DC configurations are investigated. These include four trench configurations, and two duct back configurations as described in Table 1.[5,6]

Table 1. Construction, configuration, and length of NECPL cables on DC overland route

Cable Placement	Configuration	Length (miles)
Trench	Horizontal Directional Drill,	4.97
	Maximum Trench Separation, Typical Trench Separation, and Cables Touching	50.41
Duct Bank	Configuration 1	0.71
	Configuration 2	0.01

As shown in Table 1, nearly 99% of the overland route is constructed in a Trench-type configuration. The trenched cable will be installed in one of four configurations, Horizontal Directional Drill (HDD) (reflects the beginning and end of HDD segments where the cables are separated) while the remaining three configurations represent the maximum, typical, and minimum (touching) cable separation distances within the trench. Along approximately 0.7 miles of Route 100 in Ludlow the line will be constructed in an underground duct bank, as described by Configuration 1, while Configuration 2 represents one of the three or four manholes required along the duct bank.

Trench Configurations

The general layout of the trench configurations is illustrated in the schematic diagram shown in Figure 1. The difference between the four trench configurations to be modeled is in the

[5] Two above ground attachments (crossing a bridge and a headwall of a culvert). The analyses of these configurations are provided in Appendix A.

[6] The AC duct bank configuration is proposed for approximately 0.6 miles, the analyses for which are provided in Appendix B. Approximately half of the AC duct bank route is proposed within private lands.

separation between the two cable conductors as summarized in **Error! Reference source not found.**.[7]

Table 2. Cable separations and burial depth for trench and duct bank configurations

Cable Placement	Configuration	Burial Depth (feet)	Cable Separation (center-center)	Orientation
Trench	Cables Touching	4	5.24 inches (horizontal)	East-West
	Typical Trench Separation	4	1.5 feet (horizontal)	East-West
	Maximum Trench Separation	4	3 feet (horizontal)	East-West
	HDD	4	6 feet (horizontal)	East-West
Duct Bank	Configuration 1	3.56	22 inches (horizontal)	North-South
	Configuration 2	6	2 feet (vertical)	North-South

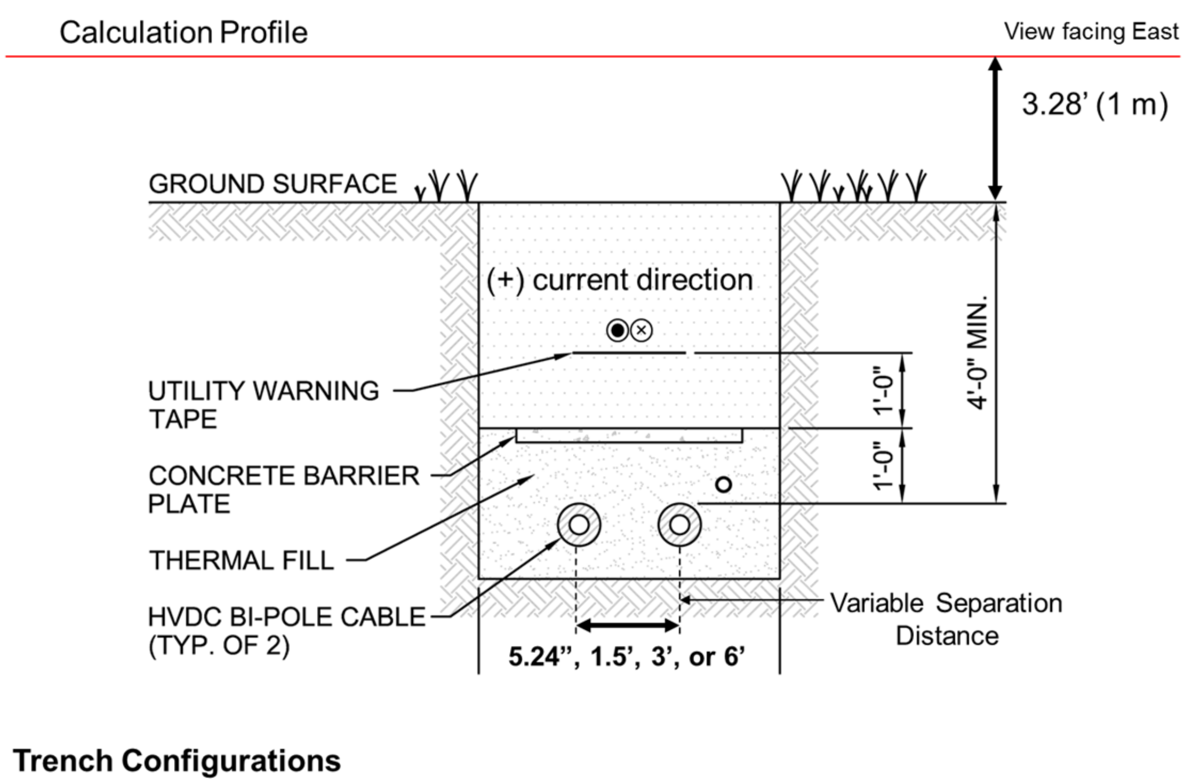

Figure 1. Underground trench configurations and location of above ground calculation profile (not to scale).

[7] For the HDD configuration, the cables are installed inside a sleeve which is directionally drilled under certain resources or infrastructure. HDD's require further separation of the cables compared to trench installation, but are buried deeper than cables in a trench.

Duct Bank Configurations

The general layout of the DC duct bank in which the conductors are arranged in a horizontal configuration (Configuration 1) is illustrated in the schematic diagram shown in Figure 2. The (+) and (-) cables will be placed in the two outside conduits with the center conduit providing space for a spare cable. The entire duct bank is assumed to be buried 3 feet, 1 inch underground. For Configuration 2, the duct bank is rotated 90 degrees so that cables and their ducts are aligned vertically over one another and separated by 2 feet; the rest of the configuration is identical to that of Configuration 1. The modeling configuration of both of the duct bank configurations including the separation between the two cable conductors are summarized in Table 2 above.

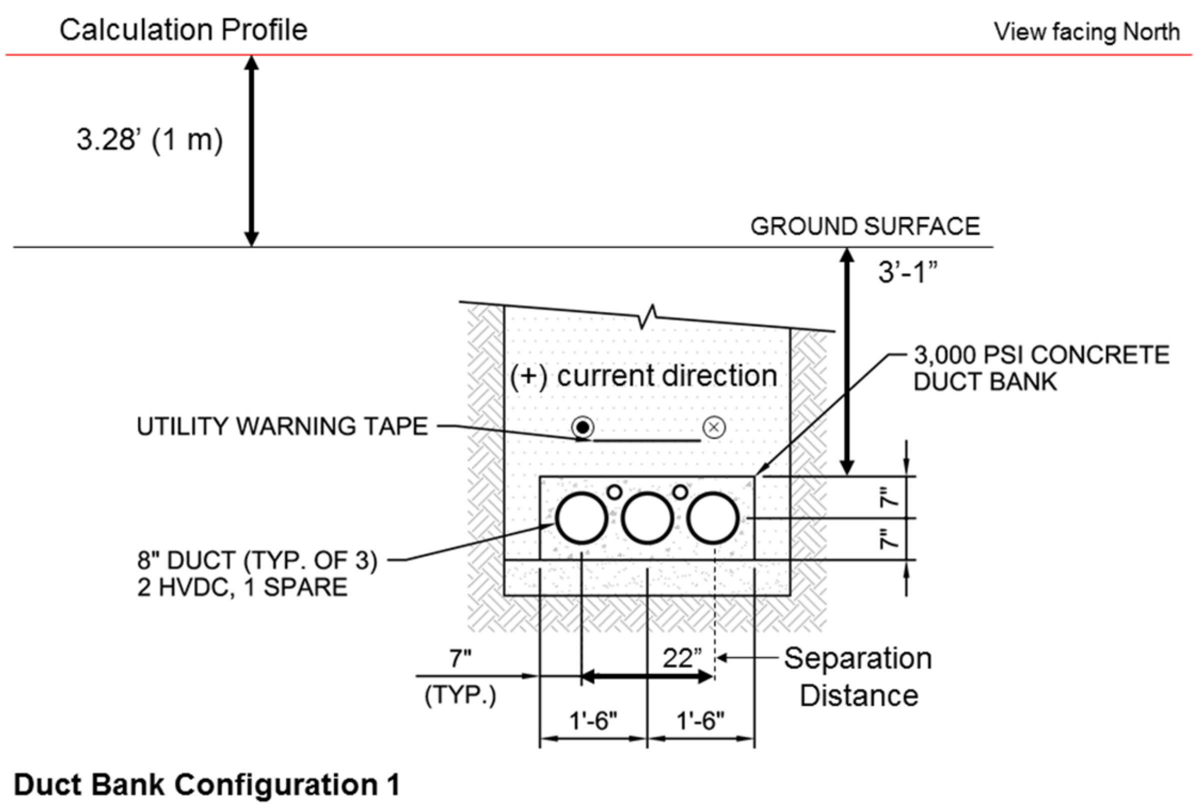

Figure 2. Underground duct bank Configuration 1 and above ground location of calculation profile (not to scale).

DC Magnetic Field Modeling

DC magnetic fields were calculated by the application of the Biot-Savart Law to the specific cable configurations for NECPL that were provided to Exponent by TDI-NE. The Biot-Savart Law is derived from fundamental laws of physics and is used to calculate the magnetic field from the flow of electric current in conductors. Application of the Biot-Savart Law is particularly appropriate for long straight conductors, such as the NECPL cables.

The modeling specifications for all six modeled configurations (in which the transmission line is installed in a trench or duct bank) are summarized in Table 2, including the modeled cable diameter of 5.24 inches.[8] These form the inputs for calculation results and discussion in the following section.

In all calculations, the loading of each of the two ±320 kV DC cables was assumed to be 1,650 amperes (A), a conservative assumption for modeling 1,000 MW of delivered power. The magnetic field expressed as magnetic flux density in units of milligauss (mG) was calculated along a transect perpendicular to the route of the cables at a height 3.28 feet (1 meter) above ground in accordance with IEEE Standards C95.3.1-2010[9] and 0644-1994.[10] The magnetic field is calculated for current in each cable flowing in both directions (i.e., both current polarities).

Since the magnetic field from the earth and from the NECPL cables are both static (i.e., they do not change significantly with time) and the magnetic field vectors (with a strength and a direction), from the NECPL cables will either increase or decrease the total magnetic field at any particular location based upon the cable orientation and current polarity. In order to show the total magnetic field and the local change of the earth's geomagnetic field due to the NECPL,

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8 The overland transmission cable has been modeled with an outer diameter of 5.24 inches, representative of the largest expected cable to be used on the overland portion of the route. If a different cable diameter were to be selected it will slightly affect the calculated magnetic field level for all DC modeling scenarios. In no case is it expected that a cable of a different size would affect the calculated magnetic field levels to a significant degree relative to the applicable ICNIRP or AAMI limits.

9 Institute of Electrical and Electronics Engineers (IEEE). IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz (Std. C95.3.1-2010). New York: IEEE, 2010.

10 Institute of Electrical and Electronics Engineers (IEEE). Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines (ANSI/IEEE Std. 644-1994). New York: IEEE, 1994.

the magnetic-field vectors from the cable along x, y, and z axes were combined with the parallel vectors of the earth's main geomagnetic field, as determined by the latest International Geomagnetic Reference Field Model (i.e., IGRF-11), for specified latitude and longitude coordinates to obtain the total resultant magnetic field.[11]

The geomagnetic field at 43.429152°N latitude and 72.698071°W latitude (approximately on the East Lake Road Bridge in Ludlow, Vermont) was used in all calculations. Along the project route, the geomagnetic field does not vary sufficiently to affect the reported magnetic field values. The components of the geomagnetic field are shown in Table 3.

Table 3. Total geomagnetic field

Component	**Geomagnetic field (in nanotesla [nT] and mG)**		
Northern component	18789.9 nT	=	187.90 mG
Eastern component	-4835.6 nT	=	-4.84 mG
Downward component	49403.5 nT	=	494.04 mG
Total geomagnetic field (norm)			530.77 mG

[11] National Geophysical Data Center (http://www.ngdc.noaa.gov/geomag/data.shtml).

Results and Discussion

Trench Configurations

The DC line is proposed to be installed in trench configurations for the majority of the overland route (approximately 99%). The total magnetic field (geomagnetic field + DC line) calculated for the trench configurations, with a 4-foot cable burial depth, horizontally adjacent cables, and eastward current in the northern cable, are presented in Figure 3, along with the ambient geomagnetic field. The magnetic field profiles are shown for the cables touching, as well as for cable separations of 1.5 feet, 3 feet, and 6 feet, representing the Typical Separation, Maximum Separation, and HDD configurations, respectively.

The total magnetic field calculated for the trench configurations, with eastward current in the northern cable are presented in Figure 3 and results with the eastward current in the southern cable are presented in Figure 4.

The largest deviations from the ambient geomagnetic field occur for the relatively infrequent HDD configuration (<10% of the overland route). In this configuration the total magnetic field will increase by a maximum of approximately 980 mG. At a distance of 25 feet to either side of the circuit centerline in the HDD configuration, the maximum deviation (positive or negative) from the ambient geomagnetic field will be 94 mG or less (an 18% change).

For the remaining trench configurations the magnetic field levels are much lower. For the Maximum Separation configuration (3 feet) the total magnetic field will increase by a maximum of approximately 550 mG (both for eastward power flow on the northern cable). For the more common Typical Separation configuration, (1.5 feet) the total magnetic field will increase by maximum of approximately 280 mG while for the cables touching, the total magnetic field will increase by a maximum of approximately 70 mG (also both for eastward power flow on northern cable). At a distance of 25 feet from the centerline of the cables, the maximum change in magnetic field level will be less than 47 mG (i.e., 8.9%).

The direction of current flow has a significant effect on the total magnetic field level both above and to the sides of the proposed trench configurations. The maximum magnetic field increase above the ambient geomagnetic field for all configurations occurs when the eastward current is flowing on the southern cable. Beyond a distance of approximately 10 feet from the cable centerline, however, the magnetic field level is less for this configuration than when eastward current is flowing on the northern cable.

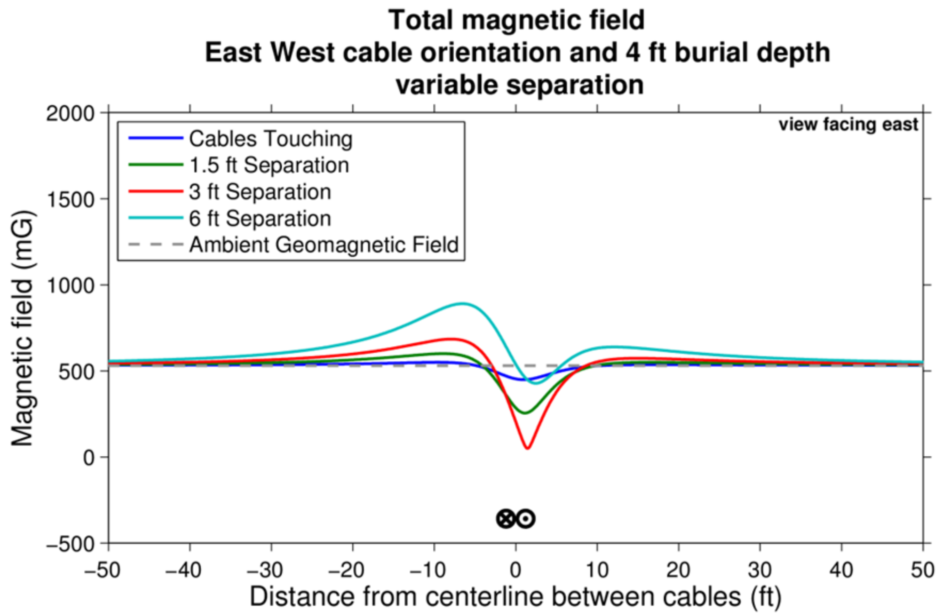

Figure 3. Magnetic field profiles (mG) for the trench configurations, above east-west oriented cables buried 4 feet, with variable separation, and eastward current in the northern cable.

The total magnetic field calculated for the duct bank configurations and both current polarities are presented in Figure 4.

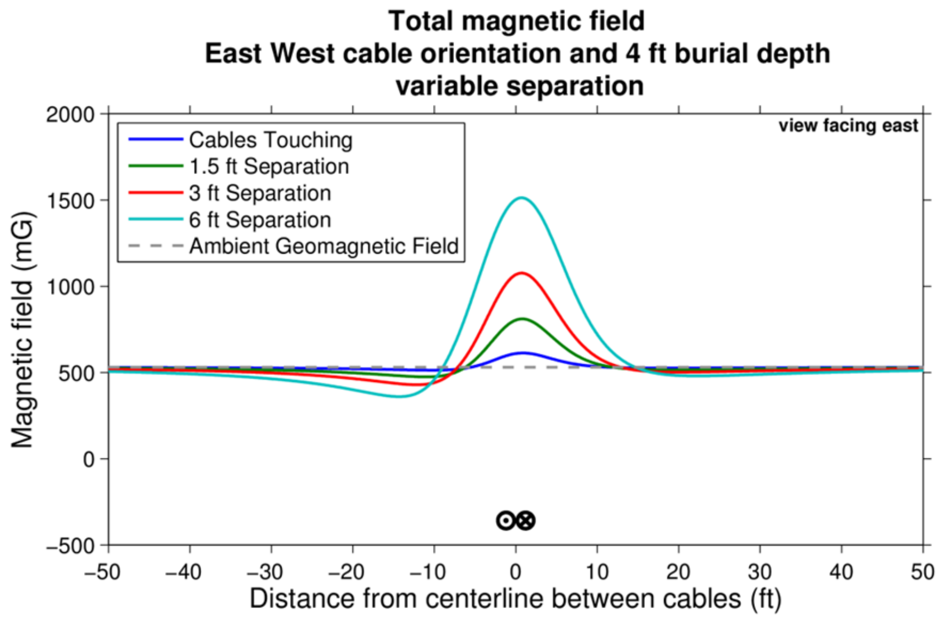

Figure 4. Magnetic field profiles (mG) for the trench configurations, above east-west oriented cables buried 4 feet, with variable separation, and eastward current in the southern cable.

Duct Bank Configurations

In a small part of the overland route (~0.7 miles, ~1%) the line is proposed to be installed in an underground duct bank. The total magnetic fields calculated for the DC duct bank Configuration 1, with a 4-foot cable burial depth, horizontally adjacent cables, and both current polarities, are presented in Figure 5. Likewise, the total magnetic field calculated for DC duct bank Configuration 2 for a 6-foot cable burial depth, vertically adjacent cables, and both current polarities, are presented in Figure 6.

Where the cables will be placed in a DC duct bank (<1% of the total overland route), the total magnetic field 1 meter above ground will increase by a maximum of approximately 400 mG, while in Configuration 2, the total magnetic field will increase by a maximum of approximately 140 mG (both for northward power flow on top cable). At a distance of 25 feet to either side of the circuit centerline in both duct bank configurations, the maximum deviation (positive or negative) from the ambient geomagnetic field will be 25 mG or less (a 4.7% change).

The direction of current flow also has a significant effect on the total magnetic field level both above and to the sides of the proposed duct bank configurations. In Configuration 1, the highest magnetic field level above the duct bank occurs for northward current flow on the eastern cable, but at 10 feet or more from the centerline of the duct bank the magnetic field level will be less than for northward current flow on the western cable. For Configuration 2, the results are similar for both current directions. For northward current flow on the top cable, the magnetic field increases on the eastern side of the cables and decreases on the western side, while for northward current flow on the bottom cable the magnetic field decreases on the eastern side of the cables and increases on the western side.

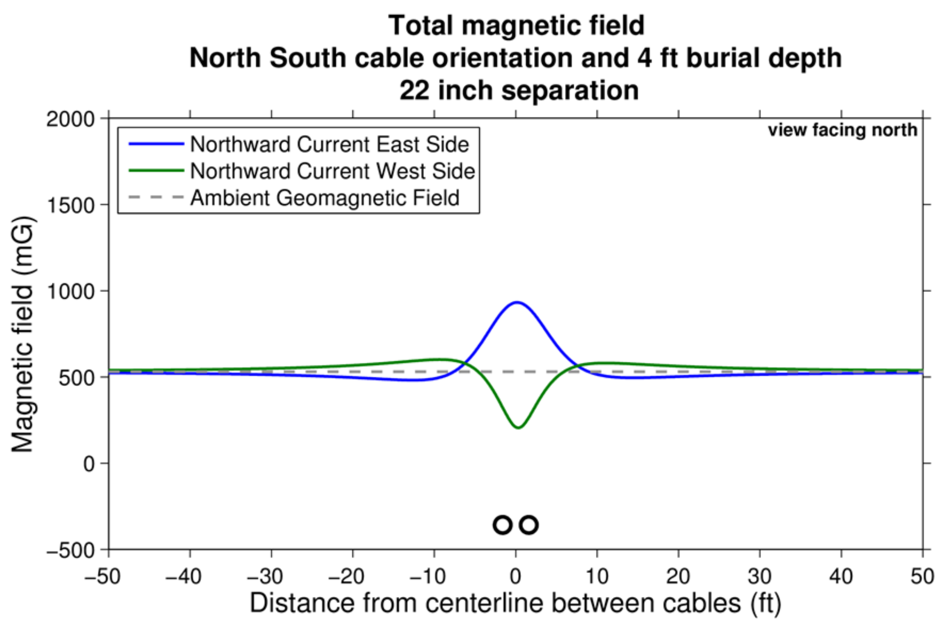

Figure 5. Magnetic field profiles (mG) for the duct bank configurations, above north-south oriented cables buried 4 feet, with 22 inch horizontal separation (both current polarities).

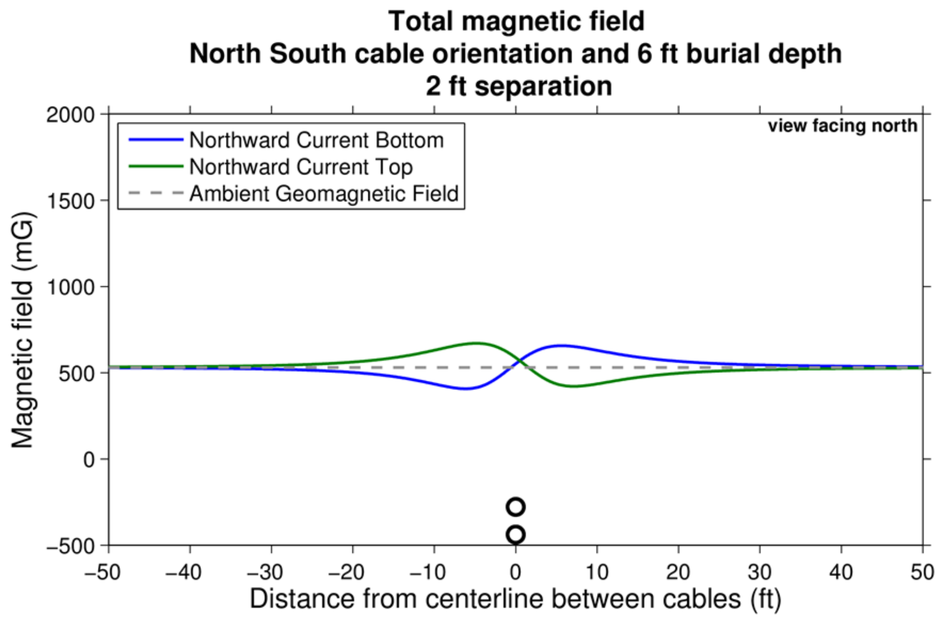

Figure 6. Magnetic field profiles (mG) for the duct bank configurations, above north-south oriented cables buried 4 feet, with 2 feet vertical separation (both current polarities).

The tabulated magnetic fields corresponding to Figure 3 through Figure 6 are summarized in Table 4. The magnetic field levels are presented as deviations from a 530.77 mG geomagnetic field magnitude.

Table 4. Magnetic field magnitude deviation (mG) from 530.77 mG geomagnetic field, 1 meter above ground and for offsets from centerline of bipolar DC circuit

Cable Placement	Current Direction	Configuration	Distance from circuit centerline -50 feet	-25 feet	-10 feet	Max + deviation	Max - deviation	+10 feet	+25 feet	+50 feet
Trench	Eastward on northern cable	Cables Touching	1.8	6.7	19	19	-82	-1.5	4.1	1.5
		Typical Separation	6.3	23	68	69	-276	1.6	14	5.0
		Maximum Separation	13	47	144	154	-481	21	29	10
		HDD	25	94	311	360	-103	101	61	20
Trench	Eastward on southern cable	Cables Touching	-1.8	-6.7	-18	82	-18	3.3	-4.0	-1.5
		Typical Separation	-6.3	-23	-55	280	-56	18	-14	-5.0
		Maximum Separation	-13	-46	-90	545	-102	57	-26	-10
		HDD	-25	-93	-71	982	-171	190	-49	-20
Duct Bank	Northward on eastern cable	Configuration 1	-7.2	-25	-41	401	-50	-17	-22	-6.8
	Northward on western cable	Configuration 1	7.2	25	69	70	-326	49	23	6.8
Duct Bank	Northward on top cable	Configuration 2	-2.3	-17	-97	126	-124	99	22	3.8
	Northward on bottom cable	Configuration 2	2.4	18	99	140	-110	-96	-21	-3.7

Summary

DC Magnetic Fields

Magnetic fields diminish quickly with distance, so the effect of the overland cables on the ambient geomagnetic field is largely restricted to a distance of approximately 25 feet on either side and above the line. The spatial extent of the magnetic field changes around the overland installation of the DC cables is greater for the trench and duct bank configurations than where the cables are installed in Lake Champlain because of the greater separation between the cables. The exception is the overland configuration where the cables are touching (as in Lake Champlain) and the spatial extent of the change in the magnetic field is largely restricted to 10 feet on either side and above the line as is calculated for the installation of the NECPL line in Lake Champlain.[12]

As illustrated above, the changes in the ambient geomagnetic field level will be largely limited to the area immediately surrounding the NECPL line. The calculated DC magnetic field deviations fall off rapidly with distance from the NECPL line, as shown in Table 4. Calculated magnetic field deviations at 25 feet from the centerline of the cables for a large majority of the overland are less than 8.9 % of the ambient geomagnetic field level. For the remaining route, the highest calculated magnetic field deviations at 25 feet from the centerline of the cables are less than 18% of the ambient geomagnetic field level.

The highest calculated level of the DC magnetic field (ambient plus cables) anywhere along the buried overland portion of the route is approximately 1,500 mG (HDD trench configuration, eastward current on southern cable). This maximum magnetic field level (calculated at 1 meter above ground, directly over the NECPL cables) is approximately 0.04% of the 4,000,000 mG general public exposure limit recommended by ICNIRP and approximately 15% of the 10,000 mG limit set by the Association for the Advancement of Medical Instrumentation's standard PC69:2007 to prevent interference to implanted medical devices. The calculated magnetic field level at the bridge attachment are lower than for the other trench configurations

[12] Exponent, Inc. Submarine Cable DC Magnetic Field in Lake Champlain and Marine Assessment. December, 2014. ExhibitTDI-WHB-2

discussed above while the magnetic field level directly over the short headwall attachment is slightly higher, approximately 1,660 mG, still a small fraction of ICNIRP or medical device standards.

AC Magnetic Fields

Calculations of the AC magnetic field performed according the methods summarized in Appendix B showed that the highest level magnetic field above the AC interconnection is less than 3% of the ICNIRP general public exposure limit for 60-Hz AC magnetic fields[13] and below general standards for implanted medical devices, such as the European Committee for Electrotechnical Standardization's (CENELEC) EN 50527-1 Standard, which specifies that the function of implanted medical devices should not be impaired at AC magnetic-field levels below 100 μT (1,000 mG).[14]

[13] International Commission on Non-ionizing Radiation Protection (ICNIRP). Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz). Health Phys 99: 818-836, 2010.

[14] European Committee for Electrotechnical Standardization (CENELEC). Procedure for the assessment of the exposure to electromagnetic fields of workers bearing active implantable medical devices - Part 1: General Std. EN 50527-1, April, 2010

Limitations

At the request of TDI-NE, Exponent calculated the magnetic field levels from a ±320-kV above ground segments of a DC transmission line that carry approximately 1,000 MW of electricity. This report summarizes work performed to date and presents the findings resulting from that work. In the analysis, we have relied on information provided by staff of TDI-NE with respect to parameters and configurations of the transmission line. The findings presented herein are made to a reasonable degree of engineering and scientific certainty. Exponent reserves the right to supplement this report and to expand or modify opinions based on review of additional material as it becomes available, through any additional work, or review of additional work performed by others.

The scope of services performed during this analysis may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented here are at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

Appendix A

Modeling of Magnetic Fields from DC Cables in a Steel Pipe Conduit

Methods

Model Configurations

At two short locations where the cable must cross a bridge and a culvert the NECPL cables will move above ground into metal conduits. In these portions of the route the NECPL transmission line is comprised of the same two cables with an outer diameter of approximately 5-inches.[1,2] The steel conduits have an inner diameter of 10.02 inches and an outer diameter of 10.75 inches. The center to center distance between the conduits is 1.25 feet as shown in Figure A-1.

Potential exposure of persons to the geomagnetic field as altered by the NECPL cables would be for very limited durations (e.g., driving or walking over the bridge or by the headwall attachment).

Bridge Attachment

The configuration of the NECPL cable for the Bridge Attachment is shown in Figure A-1. The "positive" and "negative" current directions are defined as:

- Positive current: the current in the northwestern (left-side) cable flows in the northeastern direction (into the page) and that in the southeastern (right-side) cable flows in the southwestern direction (out of the page).
- Negative current: opposite to the positive current scenario, the current in the northwestern (left-side) cable flows in the southwestern direction (out of the page) and that in the southeastern cable (right-side) flows in the northeastern direction (into the page).

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[1] The current-carrying copper conductors are 2.27-inches in diameter.

[2] The overland transmission cable has been modeled with an outer diameter of 5.24 inches, representative of the largest expected cable to be used on the overland portion of the route. If a different cable diameter were to be selected it will slightly affect the calculated magnetic field level for all DC modeling scenarios. In no case is it expected that a cable of a different size would affect the calculated magnetic field levels to a significant degree relative to the applicable ICNIRP or AAMI limits.

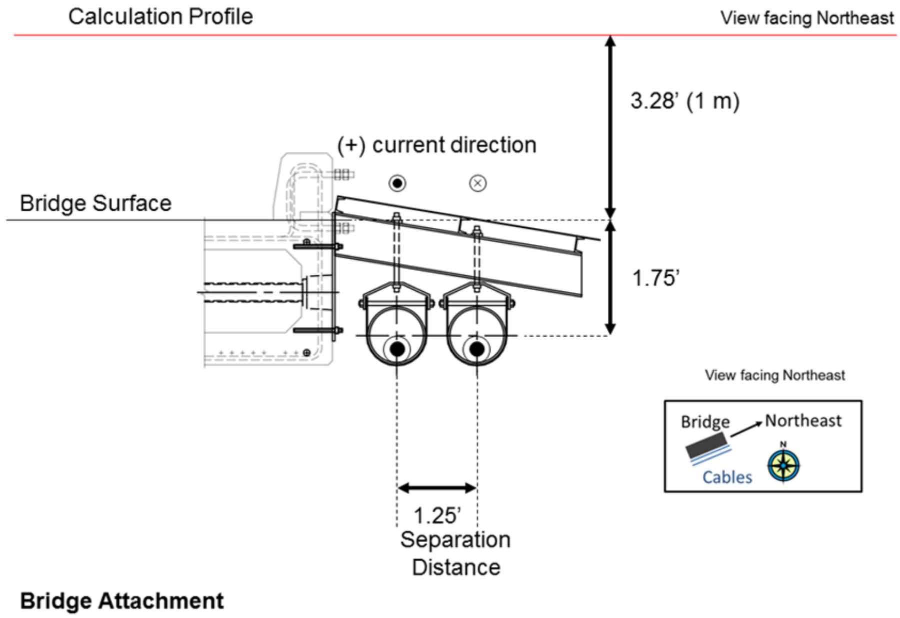

Figure A-1. Bridge Attachment configuration and location of calculation profiles (not to scale).

Headwall Attachment

The top of the headwall conduits are at ground level. Consequently, the magnetic field for the Headwall Attachment was calculated at a height of 3.28 feet above ground, as shown in Figure A-2. The current directions are defined as:

- Positive current: the current in the western (left-side) cable flows in the southern direction (out of the page) and that in the eastern (right-side) cable flows in the northern direction (into the page).

- Negative current: opposite to the positive current, the current in the western (left-side) cable flows in the northern direction (into the page) and that in the eastern (right-side) cable flows in the southern direction (out of the page).

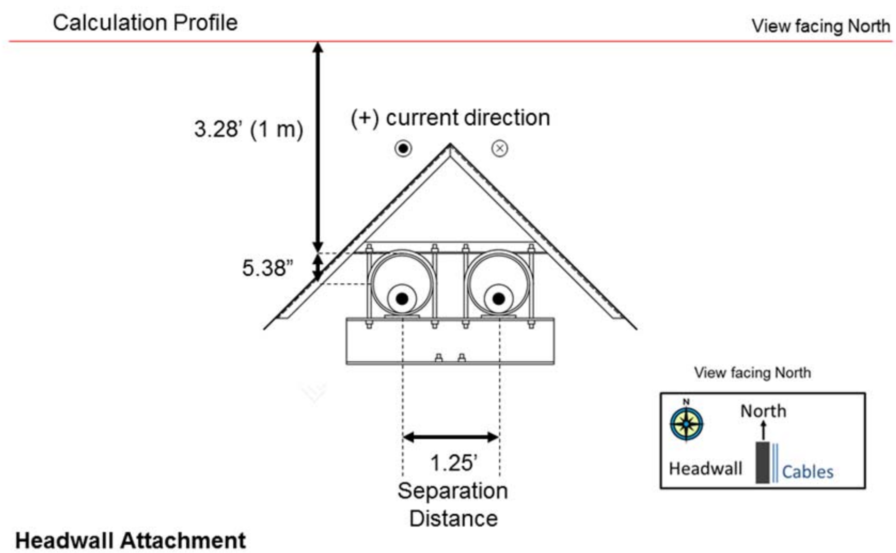

Figure A-2. Headwall Attachment configuration and location of calculation profiles (not to scale).

Finite Element Analysis Model

When the DC cables are enclosed in a metal conduit the ferromagnetic properties of the conduit must be included in the model used to calculate the magnetic fields outside the conduit. This required the application of a finite element analysis (FEA) model. FEA is a numerical technique that uses the calculus of variations to solve simple equations over numerous small subdomains (i.e., elements) in order to solve a more complex equation over a larger domain. In this investigation, the FEA is implemented using the AC/DC Module of COMSOL Multiphysics, v4.4, a commercial FEA software used to solve a variety of physics-based engineering problems.

For each attachment, the magnetic field, expressed as magnetic flux density in units of mG, was calculated along transects perpendicular to the route of the cables at a height 3.28 feet (1 meter) above the bridge surface (for the Bridge Attachment) or above ground (for the Headwall

Attachment) in accordance with IEEE Standard C95.3.1-2010 and IEEE Standard 0644-1994.[3] For each attachment and calculation position, the magnetic field was calculated for current flow on the cables in each direction. The calculated magnetic field vectors from the cables along x, y, and z axes were combined with the parallel vectors of the earth's main geomagnetic field as described in the main overland report (See Table 4). The geomagnetic field at locations considered for the bridge and the attachments to culverts is similar to that used in analyses for the underground portions of the overland route.

The detailed model developed within COMSOL is shown in Figure A-3. The same model layout is used to calculate magnetic field levels for both the Bridge and Headwall Attachments.[4] The locations of the calculation profiles are also indicated for reference.

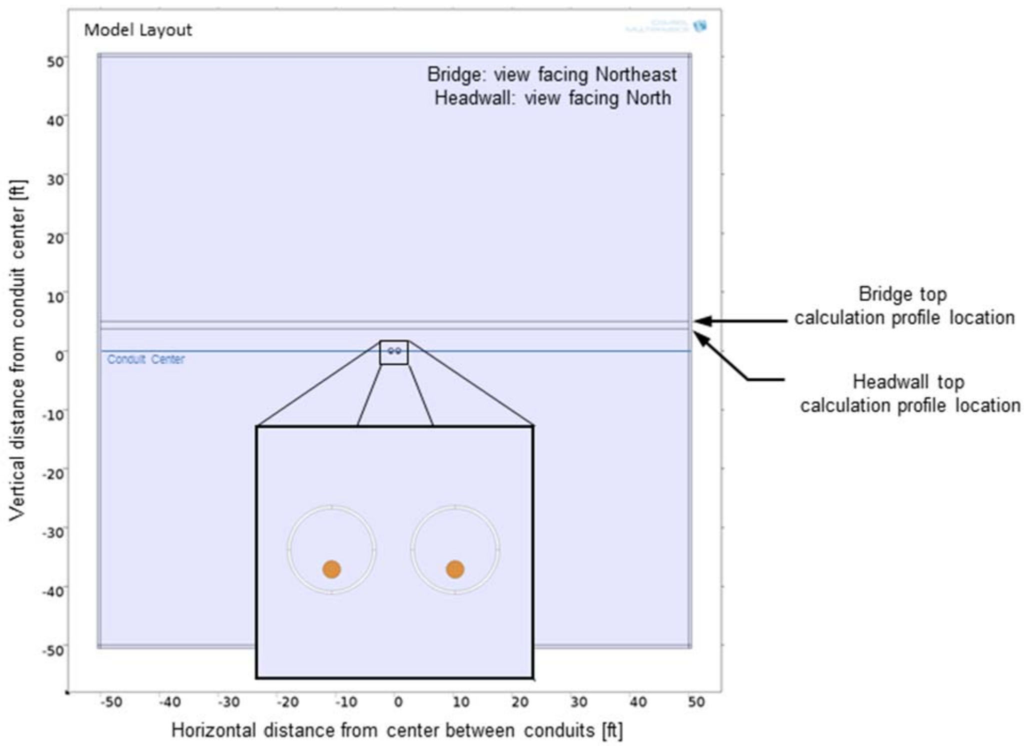

Figure A-3. Detailed COMSOL model geometry.

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3 Institute of Electrical and Electronics Engineers (IEEE). Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines (ANSI/IEEE Std. 644-1994). New York:IEEE, 1994; Institute of Electrical and Electronics Engineers (IEEE). IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz (Std. C95.3.1-2010). New York: IEEE, 2010.

4 Results of these calculations are combined with the earth's geomagnetic field separately for the Bridge Attachment and Headwall Attachment cases to account for the different geographic orientation of the cable.

The effect of the steel conduit on the magnetic field associated with the DC cables is determined by the magnetic permeability of the steel. The permeability of ASTM A 53 steel can vary based upon the carbon content of the steel and is obtained based on the permeability curve provided in Figure A-4.[5] The relative permeability of Stainless Steel (SS) is approximately equal to that of air (i.e. $\mu_{rs} \approx 1$). The relative permeability of High Permeability Steel (HPS) is set to μ_{rs} = 4088, corresponding to a carbon content of approximately 0.1%.[6]

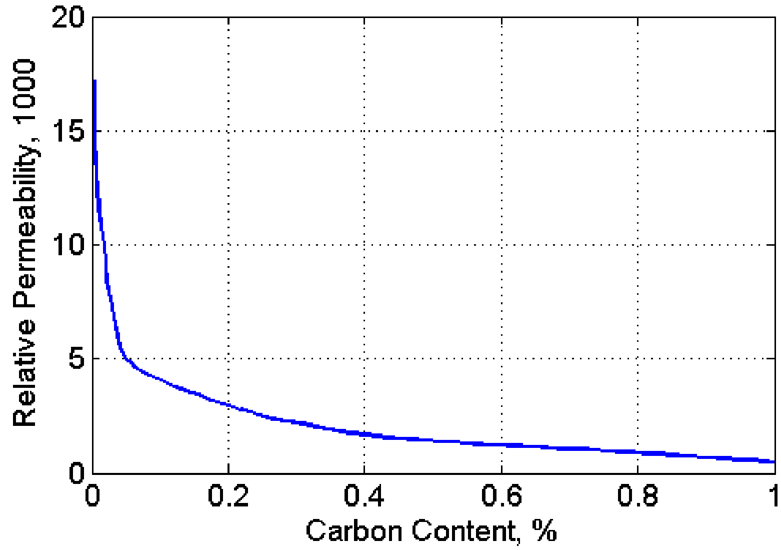

Figure A-4. Relative permeability of steel based on carbon content.

Source: Metals Handbook— Volume 1 Properties and Selection: Irons and Steels

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[5] ASM Handbook Committee. Metals Handbook— Volume 1 Properties and Selection: Irons and Steels, 9th Ed., p. 150. Metals Park, OH: American Society for Metals, 1978.

[6] The carbon content value is based on the approximate values for AISI-SAE grade 1008 steels, containing 0.06-0.08% carbon. No significant difference was observed between the results for μ_{rs} = 4088 and those obtained using μ_{rs} = 500.

Results

The calculated magnetic field strength in the vicinity of the conductors without the influence of the geomagnetic field is the same for current flow in either direction.[7] When placed within the SS and HPS, however, conduits the magnetic field around the cables differ as shown in Figure A-5a and Figure A-5b because of the differences in the magnetic permeability. In Figure A-5a, the SS conduit has a relative permeability similar to that of air and so does not have an effect on the magnetic field level inside the conduit. In contrast, the high permeability of the HPS conduit shown in Figure A-5b results in higher magnetic field levels inside the conduit itself (thus resulting in differing magnetic field levels in the surrounding medium).

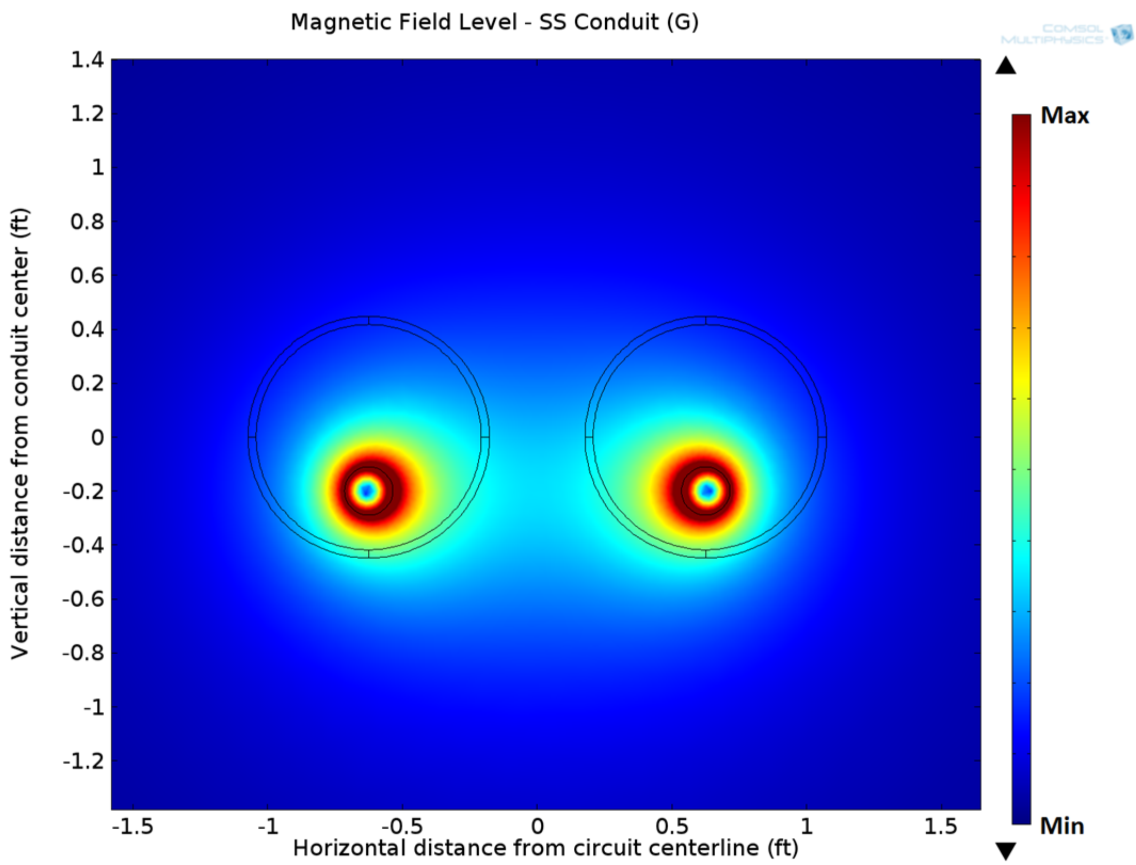


Figure A-5a. Calculated magnetic field (mG) of cables in SS conduit and magnetic field intensity in the vicinity of the conductors (current flow in either current direction).

[7] The magnitude of the results is the same in either case. The direction of the magnetic field differs among the various cases.

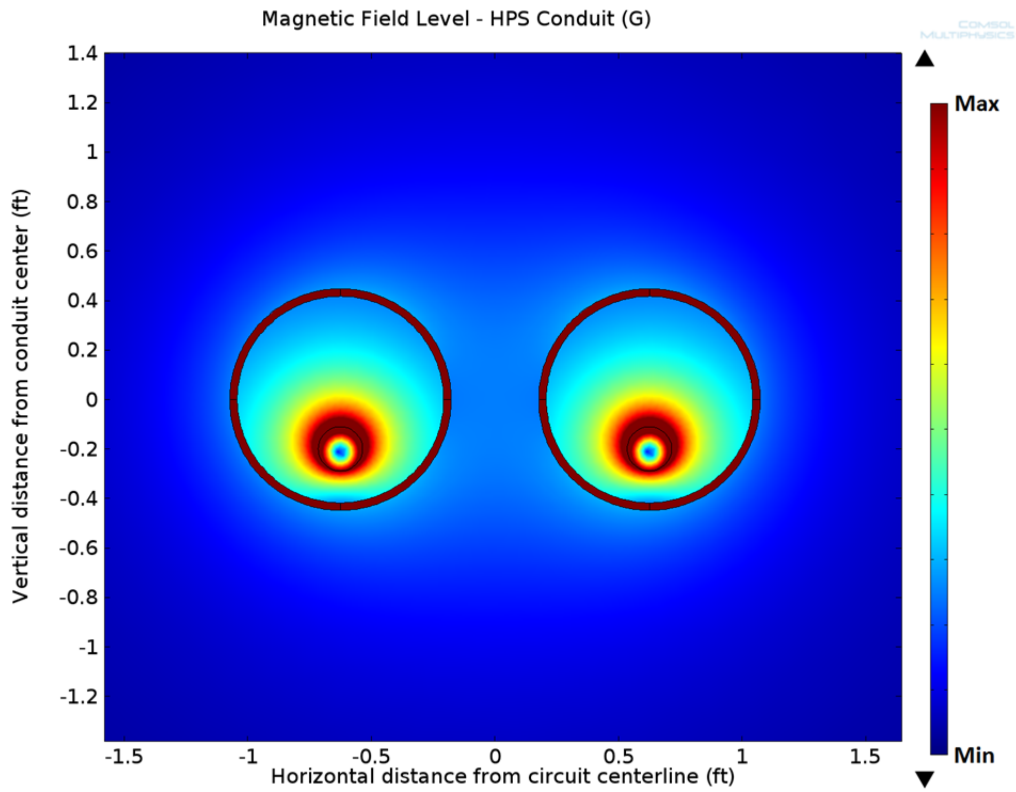
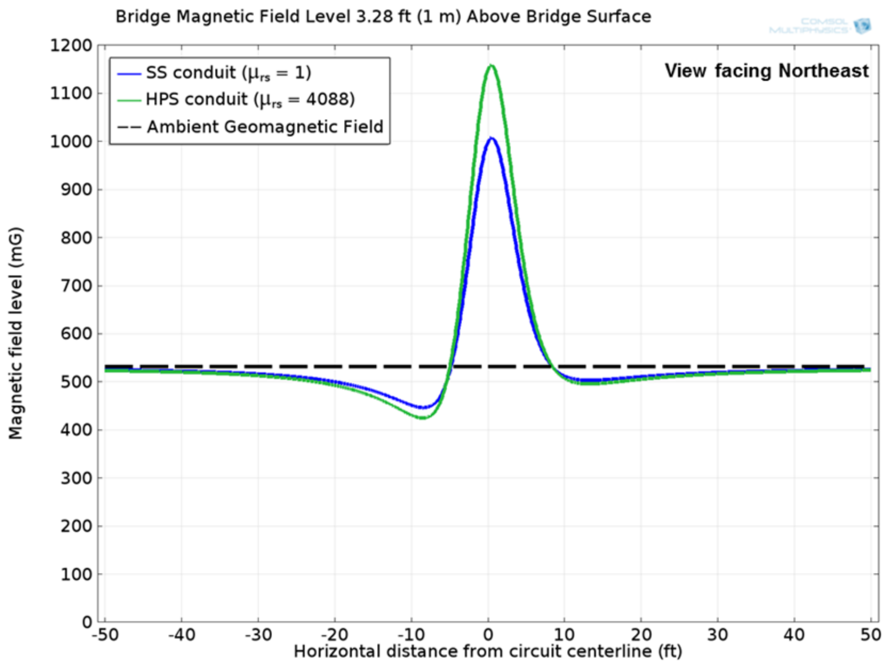


Figure A-5b. Calculated magnetic field (mG) of cables in HPS conduit and magnetic field intensity in the vicinity of the conductors (current flow in either current direction).

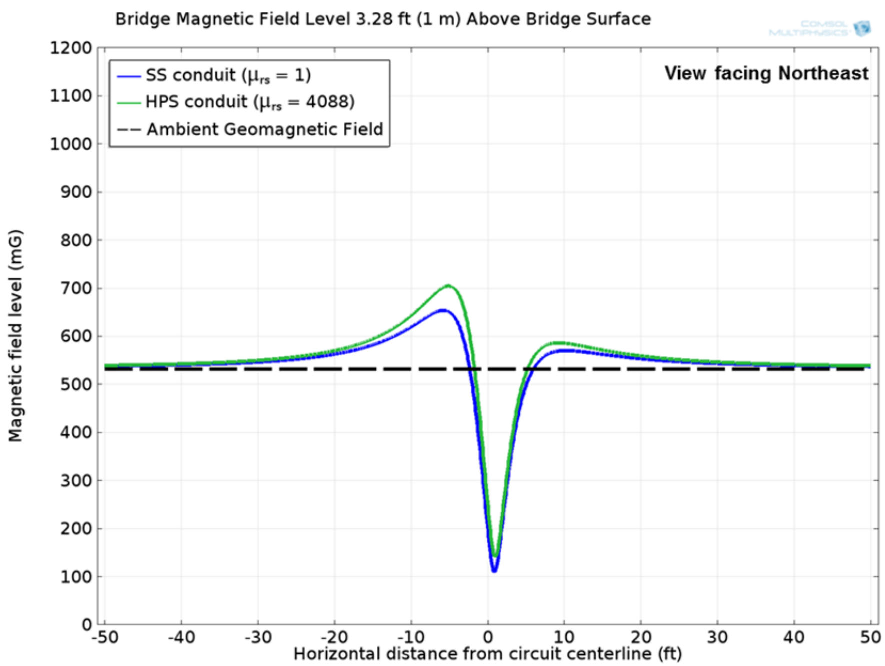
The change in the magnetic field level with horizontal distance from the cables at the Bridge Attachment and the Headwall Attachment is shown in Figure A-6 and Figure A-7, respectively.

The magnetic field level for the Bridge Attachment at 3.28 feet above the bridge surface, with positive current, is presented in Figure A-6a. As shown in this figure, for the positive current scenario (as previously defined) the magnetic field vectors of the cables and the earth are generally in the same direction over the cables, slightly increasing the total magnetic field level whereas away from the cables, the direction of magnetic field vectors from the cables is largely opposite to that of geomagnetic field, which reduces the total magnetic field. For the negative current scenario, the situation is reversed; the total magnetic field over the cables is reduced as compared to the ambient geomagnetic field (Figure A-6b), but increases further from the cables.

A similar pattern of magnetic field changes were observed for the Headwall Attachment as presented in Figure A-7a and Figure A-7b.

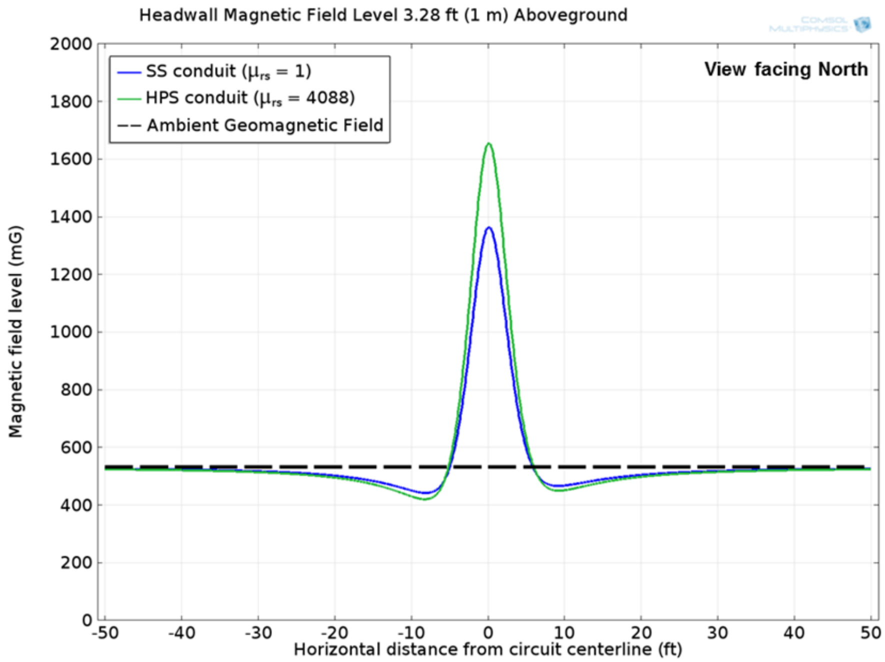


a) Positive current.

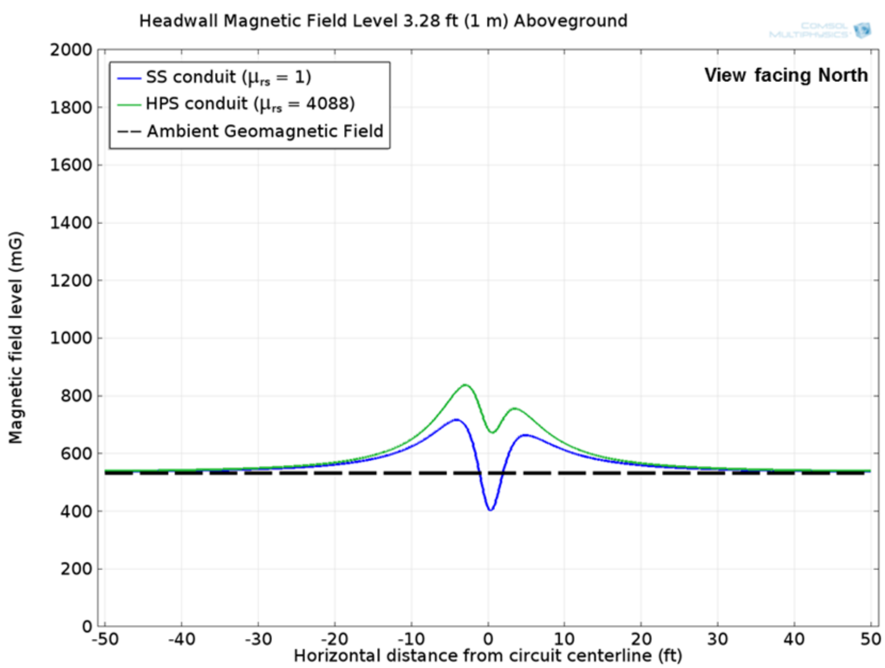


b) Negative current.

Figure A-6. Magnetic field levels 3.28 feet above bridge surface (Bridge Attachment).



a) Positive current



b) Negative current

Figure A-7. Magnetic field levels 3.28 feet above ground (Headwall Attachment).

The tabulated magnetic fields, corresponding to Figures A-6 and A-7, are summarized in Table A-1 for the eight modeling scenarios considered in this study. The magnetic field levels are tabulated as deviations from a geomagnetic field magnitude of 530.77 mG. That is, the magnetic field deviation shown is the difference between the total magnetic field and the ambient geomagnetic field alone. The calculated deviations are provided at 10 feet, 25 feet, and 50 feet to either side of the centerline of the cables, along with the maximum positive and negative deviations. As shown in Table A-1, for each of the modeled cases, the calculated total magnetic field level returns to that of the ambient geomagnetic field value (deviation of approximately 5% or less) within approximately 25 feet.

Table A-1. Magnetic field magnitude deviation (mG) from 530.77 mG geomagnetic field for offsets from HVDC circuit centerline

Attachment and calculation profile location	Conduit type	Current direction	Distance from circuit centerline							
			-50 feet	-25 feet	-10 feet	Max + deviation	Max - deviation	+10 feet	+25 feet	+50 feet
Bridge Top (3.28 feet above bridge surface)	SS Conduit	Negative	6.6	21.0	88.0	122.6	-421.6	38.8	16.0	5.9
		Positive	-6.6	-21.0	-79.8	476.7	-85.0	-19.0	-15.6	-5.9
	HPS Conduit	Negative	8.1	25.8	112.2	173.3	-389.8	54.3	19.9	7.2
		Positive	-8.0	-25.8	-100.3	627.9	-106.8	-24.3	-19.3	-7.2
Headwall (3.28 feet above ground)	SS Conduit	Negative	6.2	20.1	92.9	185.1	-129.0	80.4	19.0	6.2
		Positive	-6.2	-20.0	-81.0	833.9	-89.8	-64.1	-18.7	-6.2
	HPS Conduit	Negative	7.6	24.7	118.7	306.4	7.6	104.3	23.4	7.6
		Positive	-7.6	-24.5	-101.3	1125.9	-111.5	-80.2	-23.1	-7.6

Analysis

The proposed ±320-kV DC transmission line is proposed to be constructed in conduits hung from either a bridge or culvert headwall for very short distances. The static magnetic fields for those portions of the route were modeled for the Bridge and the Headwall Attachments. The direction of current flow on the cables is a major determinant of the magnitude of the total magnetic field around the cables relative to the background geomagnetic field. A large increase in the level of the geomagnetic field over the cables and small decreases in the total magnetic field above the level of the geomagnetic field to either side of the cables were calculated for positive current flow; conversely a large decrease in the level of the geomagnetic field over the cables was calculated for negative current flow, with smaller increases to either side.

When the conductors are placed inside a HPS conduit, the static magnetic field from the cables, at most locations, is higher than that obtained using the SS conduit. The maximum magnetic field deviation for the Bridge Attachment (at a distance of 3.28 feet above the bridge) was obtained using a HPS conduit and for the positive current scenario; the field deviation was 628 mG. The maximum deviation for the Headwall Attachment (3.28 feet above ground) was obtained using a HPS conduit and for the positive current scenario; the field deviation was 1,126 mG.

The highest calculated total static magnetic field obtained (calculated magnetic field from cables + geomagnetic field) was approximately 1,660 mG, approximately 0.04% of the 4 million mG limit for public exposure as set forth by ICNIRP[8] and approximately 17% of the pacemaker exposure standard of 10,000 mG.[9,10]

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8 International Commission on Non-Ionizing Radiation Protection (ICNIRP). ICNIRP guidelines on limits of exposure to static magnetic fields (1 Hz – 100 kHz). Health Phys 96: 504-514, 2009.

9 For devices tested to AAMI PC69:2007, no changes in the function of the pacemaker or ICD should occur up to 1 millitesla (i.e., 10,000 mG). Up to a static magnetic flux density of 50 millitesla (i.e., 500,000 mG), a pacemaker or ICD should not remain functionally affected after discontinuation of the exposure.

10 The Associate for the Advancement of Medical Instrumentation (AAMI) PC69:2007 standard has been superseded by 14117:2012, but this new standard is not yet recognized as a consensus standard by the Food and Drug Administration. There is no difference in static field values between PC69:2007 and 14117:2012.

Appendix B

Modeling of Magnetic Fields in AC Duct Bank

AC Environmental Assessment Criteria

AC transmission lines, like DC transmission lines, affect the ambient electrical environment and this section describes and evaluates the potential environmental effects of the AC transmission lines that are proposed as part of the Project. The environmental assessment criteria applied to assess these effects are standards and guidelines developed by scientific and health agencies including the International Committee on Electromagnetic Safety (ICES), the American Conference of Governmental Industrial Hygienists (ACGIH), and ICNIRP for limits of exposure to 60-Hz electric and magnetic fields. ICNIRP guideline recommendations for non-ionizing radiation, including 60-Hz magnetic fields, are formally recognized by the World Health Organization (WHO) as protective of public health. The reference values listed in Table B-1 are used as criteria for the evaluation of proposed AC transmission lines and their potential effects on the electrical environment. These standards and guidelines do not place a limit on the duration of exposure to these electrical parameters.

Table B-1. Environmental assessment standards and guidelines for AC magnetic fields

Limit	Agency providing guideline (year)	Comment
2,000 mG*	ICNIRP (2010)	General public exposure
9,040 mG†	ICES (2002)	
10,000 mG	ACGIH (2009)	Occupational exposure

* The ICNIRP (2010) occupational exposure limit is 10,000 mG.
† The ICES occupational exposure limit is 27,100 mG.

Methods

The AC duct bank circuit is modeled using the finite element analysis (FEA) method, a numerical technique, employing the calculus of variations to solve simple equations over numerous small subdomains (i.e., elements) in order to solve a more complex equation over a larger domain. In this investigation, the FEA is implemented using the AC/DC Module of COMSOL Multiphysics, v4.4, a commercial FEA software used to solve a variety of physics-based engineering problems.

The magnetic field levels are calculated at 1 meter (3.28 feet) above ground, in accordance with IEEE Std. C95.3.1-2010 and IEEE Std. 0644-1994[1] and are reported as the root-mean-square (RMS) value of the field ellipse at each location perpendicular to the center of the lines. The fields are calculated as the resultant of x, y, and z field vectors.

The magnetic field levels are calculated for the duct bank and circuit configuration, provided by TDI-NE, as shown in Figure B-1. The AC transmission line is proposed to be constructed in a split-bundle configuration where each of the three phases comprising the transmission line is split into two conductors (hence there are six total conductors, two for each phase). The duct bank contains six conduits, with an inner diameter of 8 inches, each containing one cable. The proposed transmission line is comprised of 5.14-inch diameter cables, with 2.15-inch diameter conductors. The horizontal and vertical distances between the conduits are both proposed to be 0.92 feet and each conductor is modeled to have a current load of 962 A.

In addition, a ground continuity conductor (GCC), housed in a 2-inch diameter conduit above the phase conductors is also included in modeling. The GCC is a 4/0 cable, with a conductor diameter of 0.46 inches. The current induced in the GCC by the AC magnetic field from phase conductors is obtained as part of the analysis and is included in the magnetic field calculations.

[1] Institute of Electrical and Electronics Engineers (IEEE). Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines (ANSI/IEEE Std. 644-1994). New York: IEEE, 1994; Institute of Electrical and Electronics Engineers (IEEE). IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic fields with respect to Human Exposure to Such Fields, 0 Hz to 100 kHz. New York: IEEE. IEEE Std. C95.3.1-2010.

The phasing of the conductors (ABC:CBA) was selected by TDI-NE and serves to minimize the magnetic field above the duct bank.

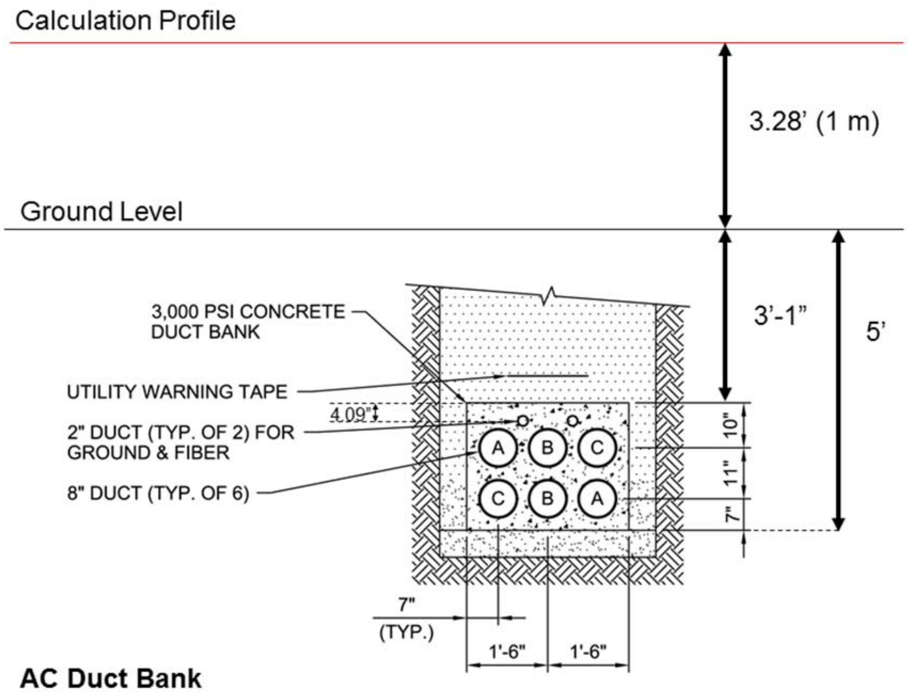

Figure B-1. AC duct bank configuration and location of the calculation profile (not to scale).

The detailed model configuration used within COMSOL is shown in Figure B-2. The location of the calculation profile is also indicated for reference.

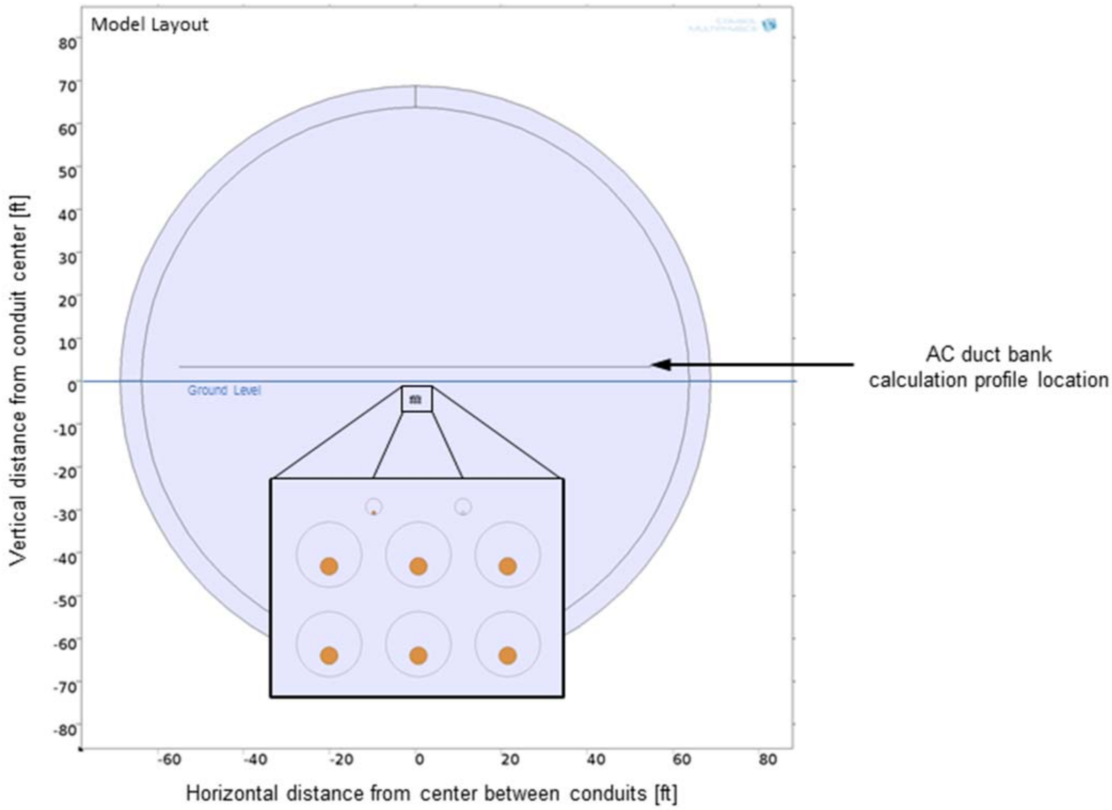

Figure B-2. Detailed COMSOL model geometry of the AC duct bank.

Results

The RMS resultant magnetic field calculated in the vicinity of the conductors is presented in Figure B-3 for the purpose of model validation. A noticeable effect due to the currents in the GCC is observed, residing in the left 2-inch conduit. The RMS current value in the conductor is calculated as approximately 48 A.

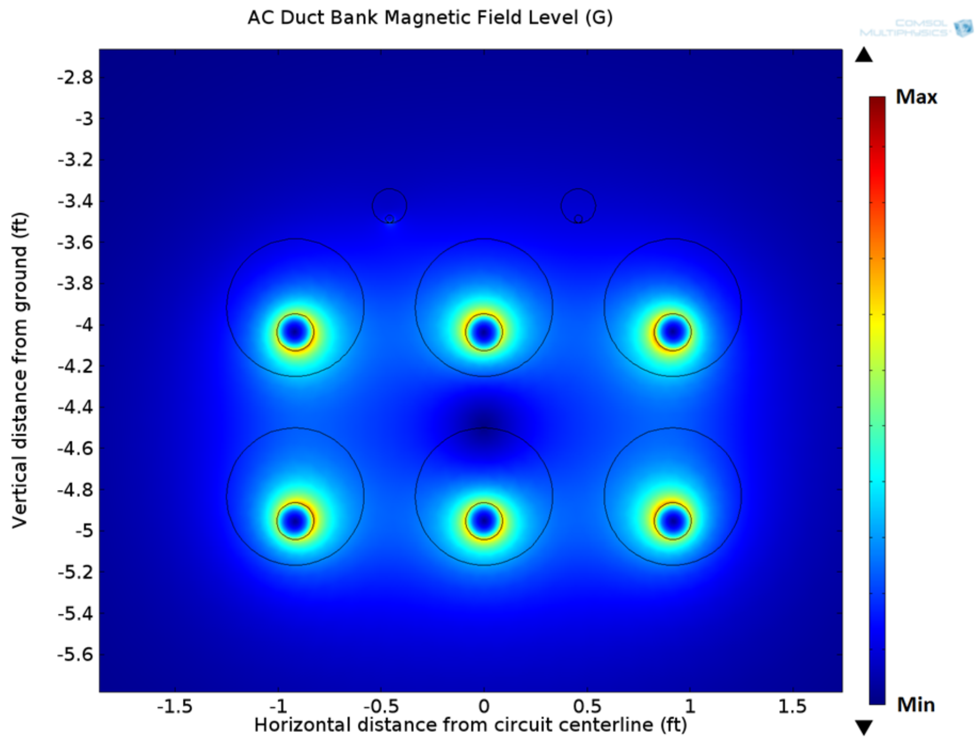

Figure B-3. Gradient of magnetic field levels in the vicinity of the conductors.

The magnetic field calculated at 1 meter (3.28 feet) above ground along a perpendicular transect, for a current loading of 962 A, is shown in Figure B-4.

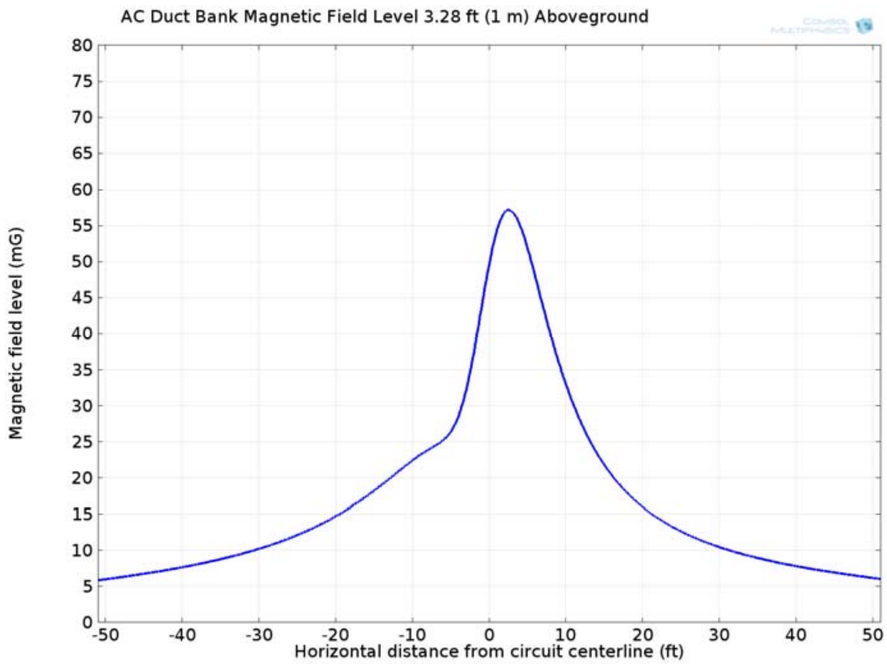

Figure B-4. Magnetic field levels 1 meter (3.28 feet) above ground (962 A current load).

The tabulated magnetic field, corresponding to Figure B-4, is summarized in Table B-2. The field levels are provided at a distance of 10 feet, 25 feet, and 50 feet at either side of the AC circuit centerline, along with the maximum and minimum values in the range of the calculated profiles. The magnetic field rapidly decreases with distance and reduces significantly within approximately 25 feet of the duct bank centerline.[2]

Table B-2. Magnetic field levels (mG) for distances from AC circuit centerline

Configuration and calculation profile location	Distance from circuit centerline						
	-50 feet	**-25 feet**	**-10 feet**	**Max**	**+10 feet**	**+25 feet**	**+50 feet**
AC duct bank (3.28 feet aboveground)	6.0	12.1	22.4	57.2	32.9	12.6	6.2

[2] The asymmetry of the calculation profile is expected and is due to the current induced in the GCC.

Analysis

The maximum magnetic field level calculated (near the center of the duct bank) was 57.2 mG. This level is less than 3% of the 2,000 mG exposure limit for public exposure as set forth by ICNIRP for 60-Hz magnetic fields. The intensity of the magnetic field at other distances was lower; diminishing to 12.6 mG within 25 feet of the duct bank centerline. The AC magnetic field levels are also below general standards for implanted medical devices, such as the European Committee for Electrotechnical Standardization's EN 50527-1 Standard, which specifies that the function of implanted medical devices should not be impaired at AC magnetic-field levels below 100 µT (1,000 mG).[3]

Although the WHO has concluded that adherence to ICNIRP exposure guidelines for magnetic fields is protective of public health, it nevertheless recommends that low-cost methods be applied to minimize AC magnetic fields from new power lines. For this Project, TDI-NE has proposed to install the conductors close together and has selected optimal phasing to facilitate mutual cancellation of the magnetic field from the conductors, consistent with the WHO's recommendation.

[3] European Committee for Electrotechnical Standardization (CENELEC). Procedure for the assessment of the exposure to electromagnetic fields of workers bearing active implantable medical devices - Part 1: General Std. EN 50527-1, April, 2010.