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October 12, 2017

Stephen August, Presiding Officer
Energy Facilities Siting Board
One South Station, 5th Floor
Boston, MA 02110

Re: New England Power Company d/b/a National Grid, EFSB 13-2/D.P.U. 13-151/152

Dear Mr. August:

Pursuant to the Final Decision of the Energy Facilities Siting Board issued on November 14, 2014, I am writing on behalf of New England Power Company d/b/a National Grid to provide a report on the efficacy of electric and magnetic field mitigation provided by passive loops, as required by Condition M of the Final Decision.

I have attached a Certificate of Service. Thank you for your attention to this matter.

Very truly yours,

David S. Rosenzweig

Enclosure

cc: Service List, EFSB 13-2/D.P.U. 13-151/152

COMMONWEALTH OF MASSACHUSETTS
ENERGY FACILITIES SITING BOARD

Petition of New England Power Company d/b/a National Grid for Approval to Construct and Operate Two New Underground 115 kV Transmission Lines and Related Upgrades to Two Existing Substations Pursuant to G.L. c. 164, § 72	)	D.P.U. 13-2/D.P.U. 13-151/152

CERTIFICATE OF SERVICE

I certify that I have this day served the foregoing upon the Energy Facilities Siting Board and the Service List in the above-docketed proceeding in accordance with the requirements of 980 C.M.R. 1.03 (Siting Board's Rules of Practice and Procedure).

Erika J. Hafner

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Dated: October 12, 2017

Exponent®

Electrical Engineering and Computer Science Practice

Evaluation of Passive Loops and Magnetic-Field Reduction at Manholes from the National Grid Canal Street to Salem Harbor 115-kV Underground Circuits

EFSB 13-2/D.P.U. 13-151/D.P.U. 13-152

Evaluation of Passive Loops and Magnetic-Field Reduction at Manholes from the National Grid Canal Street to Salem Harbor 115-kV Underground Circuits

EFSB 13-2/D.P.U. 13-151/D.P.U. 13-152

Prepared for

Transmission & Distribution Services
Burns & McDonnell
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Prepared by

Exponent
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Bowie, MD 20715

October 12, 2017

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Limitations

At the request of Burns & McDonnell, Exponent modeled and evaluated the magnetic field associated with National Grid's Canal Street to Salem Harbor 115-kV Transmission Line project. This report responds to the request of the Energy Facilities Siting Board that National Grid report to assess the efficacy of passive loop mitigation, assess the consistency of measurements with information provided in its Petition, and identify measures that could further reduce magnetic-field levels at manhole approaches. In the analysis, we have relied on transmission line design geometry, usage, specifications, and various other types of information provided by the client. We cannot verify the correctness of this input data, and we rely on the client for the data's accuracy. Although Exponent has exercised usual and customary care in the conduct of this analysis, the responsibility for the design and operation of the project remains fully with the client.

Exponent's scope of work included assessing the magnetic-field levels associated with various underground transmission line configurations provided by Burns & McDonnell. In some cases, this includes effects on magnetic fields due to the addition of passive loops. Exponent's scope of work did not include an evaluation of technical or operational issues beyond modeling magnetic-field levels.

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 investigation may not adequately address the needs of other users of this report, and any reuse of this report or its findings, conclusions, or recommendations presented herein 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.

Executive Summary

The New England Power Company d/b/a National Grid (the Company) has replaced two existing alternating current 115-kilovolt (kV) underground lines (S Cables and T Cables) between the Canal Street Substation and the Salem Harbor Substation in Salem, Massachusetts. These cables were installed in a double-circuit duct bank along a new roadway route.

The Massachusetts Energy Facilities Siting Board (EFSB) approved the project subject to conditions, including Condition M, which directed the Company to install passive loops at manhole approaches to reduce the magnetic field and to report to the Siting Board on the efficacy of this mitigation, assess the consistency of measurements of magnetic fields with information provided in its Petition, and identify measures that could further reduce magnetic-field levels at manhole approaches.

Post-construction measurements indicate that the passive loops installed as part of the project mitigated the peak magnetic field at manholes by approximately 20–27%. At a distance of ±25 feet, the passive loops had a weaker effect, reducing the magnetic field by 0–19%.

The peak measured magnetic field above the duct bank was higher than estimated from the conceptual model used to calculate magnetic fields in the Petition. However, at distances approximately ±25 feet from the centerline where structures are more likely to be located near some manholes, the measured magnetic-field levels were similar to those calculated by the conceptual model in the Petition.

Differences between measurements and calculated magnetic-field levels presented in the Petition reflect differences between as-built and operational conditions in this project and the conceptual design assessed in the Petition. These differences include asymmetric passive loops, phase imbalance of transmission lines, unequal loading of the S and T Cables, as well as phase and magnitude shifts in the ground continuity conductor currents.

Introduction

The Massachusetts Energy Facilities Siting Board (EFSB) issued its Final Decision in Dockets EFSB 13-2/ D.P.U. 13-151/ D.P.U. 13-152 on November 14, 2014, and approved the Petition of the New England Power Company d/b/a National Grid (the Company) for Approval to Construct and Operate Two New Underground 115 kV Transmission Lines and Related Upgrades to Two Existing Substations. The approval was subject to conditions, including Condition M:

> The Siting Board directs the Company to install uncompensated passive loops at manhole approaches and to file a report with the Siting Board on the efficacy of this mitigation following one year of Project operation. The report should identify whether the measurements [of magnetic fields] are consistent with information previously provided by the Company, and if they do not, identify what measures can be made to further reduce the magnetic fields. (p. 106)

This report is filed in compliance with the Board's Condition M and summarizes 1) measurements and calculations that describe the efficacy of the passive loops, 2) an analysis of the consistency with magnetic-field information provided in the filing, and 3) assessment of potential measures to further reduce magnetic-field levels outside the entrances to manholes along the route of the two underground 115-kilovolt (kV) transmission lines.

Passive Loop Concept

The methods that have been proposed to minimize magnetic fields from power lines include a passive loop (Walling et al. 1993)[1], which is a de-energized loop of conducting wire placed in proximity to the power line. The magnetic field from the power line passing through the wire loop induces a current flow in the loop that in turn generates a magnetic field with a direction opposite to that of the power line (Lenz's Law). Magnetic fields from sources with opposite direction will partially cancel each other.

1 Walling, R.A., J.J Paserba, and C.W. Burns. Series-capacitor compensated shield scheme for enhanced mitigation of transmission line magnetic fields. IEEE Transactions on Power Delivery. 8:461–469, 1993. doi:10.1109/61.180369.

The operation of passive loop shielding is determined by the fundamental physical principles embodied in Faraday's Law and Lenz's Law that describe the amount of voltage and current induced in a loop by an impinging magnetic field. The efficacy of the passive loop in canceling the magnetic field is determined *inter alia* by the induced *current* that flows in the loop. The magnitude and phase of the induced current are determined by the loop impedance, which is a function of the loop geometry relative to the transmission lines (i.e., mutual- and self-inductances) and the material properties of the wire (resistivity).

Passive loops are best suited to situations in which moderate reductions of magnetic fields are desired and when mitigation is desired for a specific area of interest. Traditional passive loop designs can reduce magnetic-field levels by as much as ~50%; have a relatively low impact on transmission circuit ampacity and a relatively low cost; and, if cables are accessible without excavation, can be installed around existing lines (Evo et al. 2017)[2]. For operational, construction, and economic reasons, passive loops are applied to specific limited areas of interest. In this project, the area of interest is the approach where the two parallel lines separate to enter a manhole vault. Passive loops are generally not the preferred solution, however, where magnetic fields are proposed to be mitigated along extended portions of the transmission line route. In such circumstances, alternatives such as phase optimization or increasing transmission line depth (or height) may prove viable options.

Application of Passive Loop Concept to Manhole Vaults

In Appendix 5-2 of the Petition to the EFSB (Exponent 2013)[3], hereafter referred to as the Petition, Exponent described the magnetic fields expected during project operation. The highest calculated magnetic fields were found on portions of the route where the two circuits separated to enter their respective manhole vaults.

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2 Êvo MTA, de Paula H, José S. Lopes IJS, Mesquita RC, Souza DSC. Study of the influence of underground power line shielding techniques on its power capability. J Control Autom Electr Syst 28:541–551, 2017. DOI 10.1007/s40313-017-0319-x.

3 Exponent. Evaluation of Magnetic Fields from the National Grid Canal Street to Salem Harbor 115-kV Underground Circuits. September 3, 2013 Appendix 5-2 to Petition.

In the Petition, Exponent estimated from a conceptual model that, at the minimum burial depth of 3.8 feet and full load of 250 megavolt-amperes (MVA) for both S and T Cables, the magnetic fields at the manhole entrances would be 143 milligauss (mG) over the cables and 27–30 mG ±25 feet from the circuit centerline (Exponent 2013, p. 18). Exponent also estimated that with the addition of a passive loop on the outside of each transmission line at the manhole entrance, the magnetic fields at these same locations would be 71 mG and 24–26 mG, respectively (Exponent 2013, p. 24). Thus, installation of the passive loops was estimated to result in a reduction in the maximum calculated magnetic field of approximately 50% and a reduction of approximately 11–13% at ±25 feet from the transmission line centerline. Figures 7, 13, and 17 as well as excerpts from Tables 1, 5, and 6 from the Exponent 2013 report are provided in Appendix A for ease of reference.

In light of the above results, the Company proposed installing passive loops along the approaches to the six manholes, which made up a small percentage of the route. Passive loop mitigation was targeted at those limited locations where unmitigated magnetic-field levels were expected to be highest. The proposed mitigation was experimental but offered a reduction in the highest fields at a reasonable cost. The EFSB accepted the Company's proposal with conditions.

Measurements and Modeling

Condition M requests two separate analyses. The first assesses the efficacy of the passive loops, accomplished here by comparing the magnetic-field levels calculated by the as-built model (validated through measurements) with and without passive loops. The second compares the post-construction measurements of magnetic-field levels to those calculated for the conceptual project design as provided in the Petition. To provide these analyses, multiple measurements of resultant[4] magnetic fields were made at each manhole as well as at locations between manholes where the transmission lines are installed in a horizontal dual-circuit duct bank. All measurements of magnetic fields in this report were made with calibrated instruments and certificates of calibration for these instruments are attached in Appendix G.

A schematic indicating the location of each measurement is shown in Figure 1. Manholes are shown by purple boxes labeled 1 through 6 sequentially going from the Canal Street Switchyard to the Salem Harbor Substation. At each manhole, there are two manhole vaults, one for each circuit. Manhole 1 and Manhole 6 are shown expanded and illustrate that the S and T Cables separate and enter separate manhole vaults. There are four passive loops (illustrated in red) at each manhole:

1. adjacent to the S Cables entering the manhole vault;
2. adjacent to the S Cables exiting the manhole vault;
3. adjacent to the T Cables entering a separate manhole vault; and
4. adjacent to the T Cables exiting the manhole vault.

Appendix B presents an extended discussion of the configuration of the transmission lines and passive loops at manholes.

Measurements to assess the efficacy of the passive loop were performed at the manholes closest to the substations (i.e., the Canal Street side of Manhole 1 and the Salem Harbor side of Manhole 6), the only locations where the ground continuity conductors (GCCs)

[4] Resultant magnetic fields are a way of expressing the magnetic-field vectors aligned along orthogonal x, y, and z axes as a single value.

are safely accessible without multiple line outages.[5] These locations are designated 1a and 6b, respectively, and are shown by green arrows in Figure 1. The protocol for the measurement of currents on GCCs is described in Appendix C.

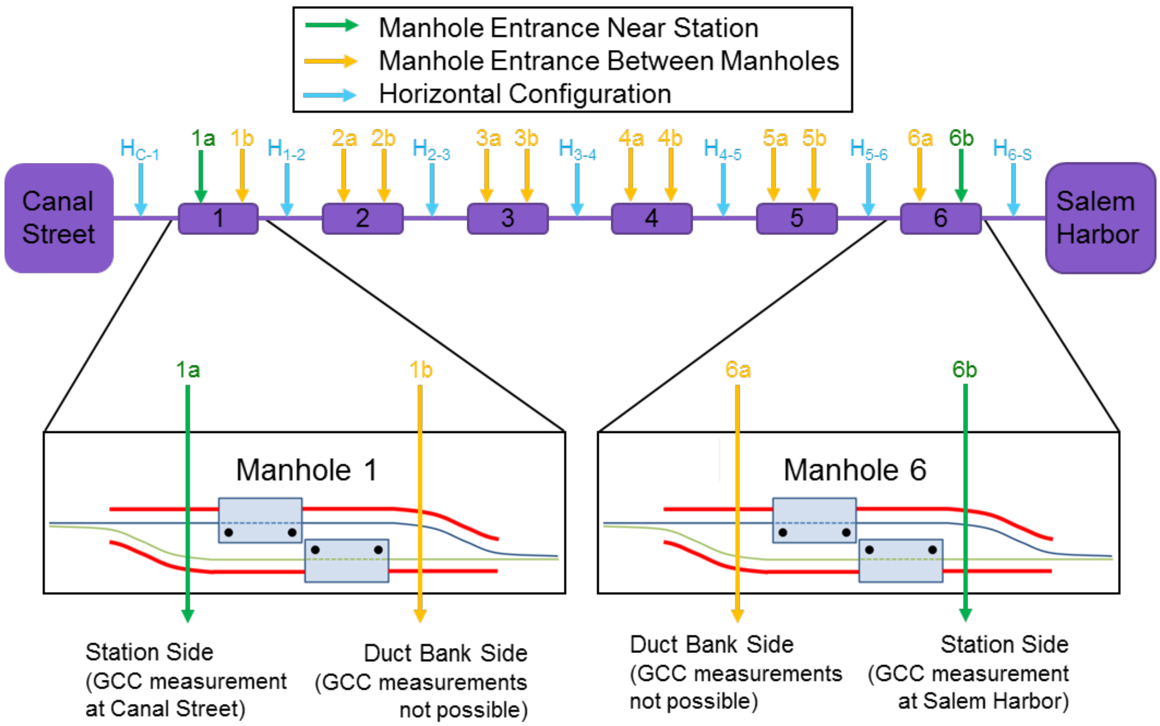

Figure 1. Overview of measurement locations

Measurements of magnetic fields were taken for comparison to magnetic-field values derived from the conceptual model in the Petition at the approaches to the manholes (two measurements each) as shown by the yellow arrows in Figure 1. In addition, measurements also were made over portions of the route installed in the "typical" horizontal configuration between each set of manholes at locations indicated by the teal arrows in Figure 1.

At each location, Exponent took measurements starting on one side of the duct bank, proceeding transversely across the duct bank to the other side along a transect at least

[5] GCCs are installed to prevent shocks and provide an alternative path for fault currents that would otherwise pose a safety hazard and degrade the transmission cables. Measurements of GCC currents were necessary for calculating the efficacy of passive loops. An extended discussion of this requirement is included in Appendix C.

25 feet to either side of the duct bank centerline (farther where accessible). For all measurements, distances from duct bank centerline and magnetic-field levels were recorded simultaneously. The measurement methods and instrumentation were consistent with relevant standards published by the Institute of Electrical and Electronics Engineers (IEEE Std. 1308-1994, IEEE Std. 644-1994 [R2008], IEEE Std. C95.3.1, 2010). Details regarding the measurement methodology for each type of measurement are provided in Appendix C along with an aerial map indicating the location of each measurement.

Efficacy of Passive Loops

Passive loops, once installed, cannot safely be turned on and off without a line outage. Therefore, to assess the efficacy of the passive loops, Exponent developed and validated as-built models for Manholes 1 and 6 to calculate magnetic fields based on current levels on each conductor and the GCCs. After validating the models with measurements, the models were used to calculate the reduction in magnetic fields associated with the installation of the passive loops.

Development and Validation of As-Built Models

The magnetic fields measured at the approach to the western side of Manhole 1 and the eastern side of Manhole 6 (Locations 1a and 6b) are shown in Figure 2. Also shown is the resultant magnetic field calculated from as-built specifications of the conductors and loops and the loading of the S and T Cables and GCC currents recorded at the time of measurement.[6] At the time of measurement, the loadings on the S and T Cables were approximately 63 MVA and 59 MVA, respectively. Both profiles show a good agreement between the measured resultant magnetic field and the magnetic field calculated from the as-built drawings and using measured currents on phase conductors and GCCs.

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6 All modeling in this report was performed using COMSOL Multiphysics Version 5.3.

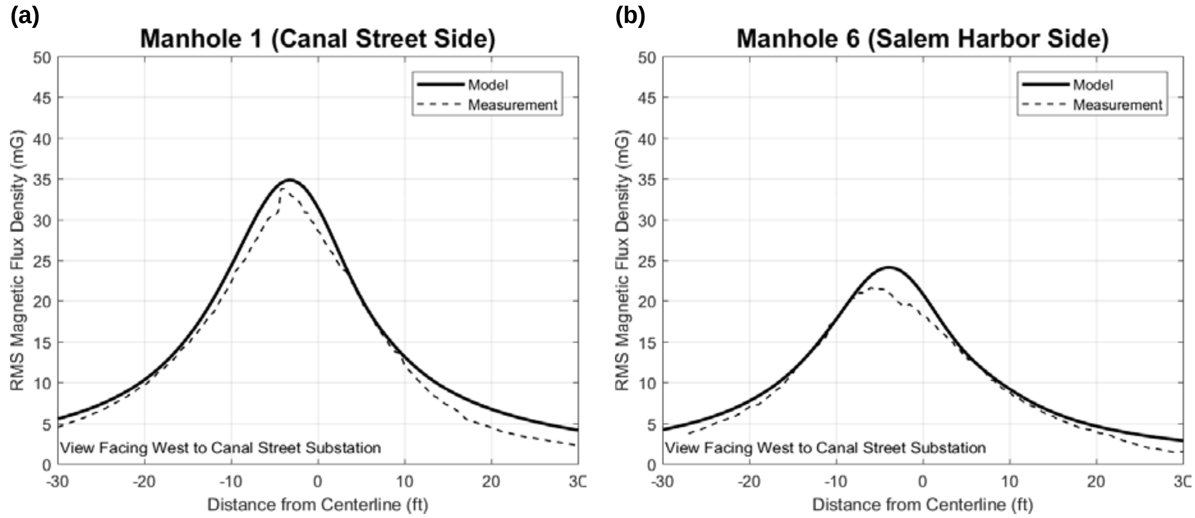

Figure 2. Comparison of as-built modeled magnetic fields to measured magnetic fields

Comparisons of the measured and modeled magnetic-field levels indicate the following:

- The agreement between measured and calculated values is good with a mean absolute error of 1.5 mG and 0.97 mG for profile 1a and 6b, respectively, and the correlation between the measured and modeled values is greater than 0.99 for both duct banks, indicating a strong linear relationship.
- The maximum magnetic fields over cables are similar with a maximum absolute error of 1.0 mG or 2.4 mG between modeling and measurements for measurements 1a and 6b, respectively. Furthermore, as shown in Appendix D, the profiles of the transverse, vertical, and longitudinal components of the magnetic field that comprise the peak fields are also similar.
- The decrease in magnetic field with distance, an indication of match between model and measurements, is as expected and, at ±25 feet, the difference between measured and calculated values varies from 0.8 mG to 2.0 mG.
- Measured magnetic fields over the duct bank were slightly lower than calculated because of small variances between the idealized model of the manhole duct banks and the as-built installation.

These results show that the computations of the magnetic field for the as-built model are confirmed by measurements.

Evaluation of Passive Loops

The as-built models for Manholes 1 and 6 were used to assess the efficacy of the passive loops at these locations by using the validated model and comparing magnetic fields modeled with and without the passive loops. The profiles in Figure 2a and Figure 2b show the measured magnetic-field levels (thin dashed line) and the magnetic-field levels calculated using the as-built geometry and loading at the time of measurements (thick black line). To assess the efficacy of the passive loops, the passive loops were removed from the as-built model with the results plotted in the brown lines in Figure 3a and Figure 3b. These comparisons indicate the following:

- Passive loops attenuate the peak magnetic field above the manhole approach by 20–27%.
- Passive loops have a weaker effect at ±25 feet from the manhole centerline, reducing the magnetic field by 0–19%.
- The performance of the passive loops at the maximum was less than expected from the conceptual model (20–27% reduction versus 50%).
- The performance of the passive loops at ±25 feet from the manhole centerlines was similar to that expected from the conceptual model (0–19% reduction versus 13%).

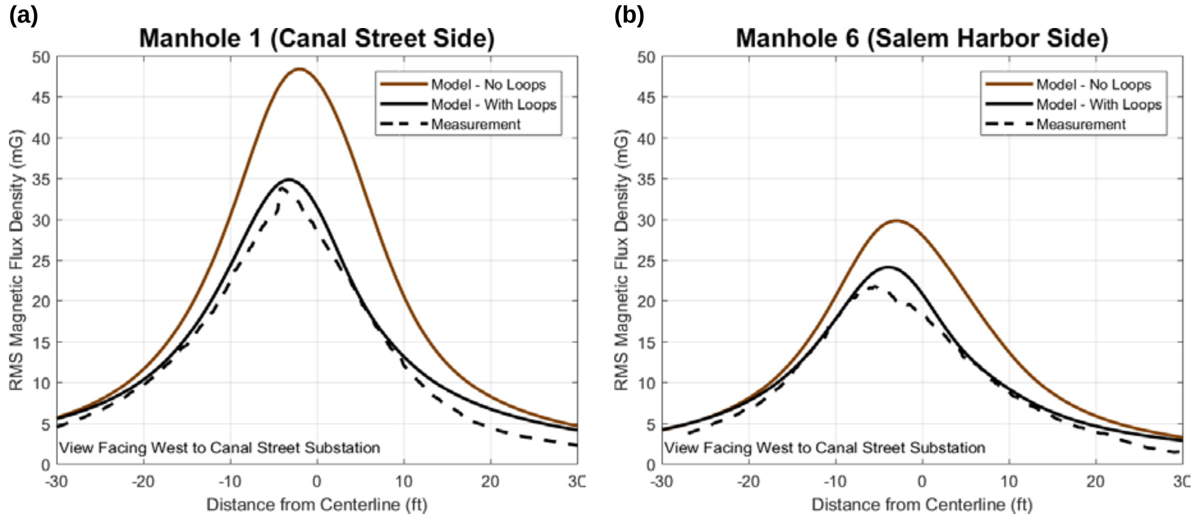

Figure 3. Efficacy of passive loops. (a) At Manhole 1 (Location 1a), the calculated reduction in the magnetic field above the duct bank is 27% due to the passive loops. (b) At Manhole 6 (Location 6b), the calculated reduction in the magnetic field above the duct bank is 20% due to the passive loops.

The above analysis illustrates some general points: 1) the mitigation provided by the passive loops is limited to portions of the area above and adjacent to the passive loop; 2) the magnitude of magnetic-field reduction achieved is greatest closer to the source and loop; 3) the magnitude of the reduction achieved by the loops diminishes with distance, with field levels ultimately returning near to those that would be observed without a passive loop; and 4) the efficacy achieved is influenced by multiple installation and operational conditions that may diminish the expected effectiveness of the passive loops.

Comparison to Application Values

In addition to assessing the efficacy of passive loops, Condition M also requires comparing magnetic-field levels measured post-construction to the calculated magnetic-field levels provided in the Petition. As an initial matter, the magnetic-field levels measured post-construction were far lower than the magnetic-field levels at 250 MVA presented in the Petition, ranging from 10–40 mG directly over the manhole approaches and 8–16 mG directly over the horizontal configuration, with much lower fields ±25 feet from the centerline of the duct bank.

However, to meaningfully compare the measured magnetic fields to those calculated in the Petition, the differences between the loadings on the lines at the time of measurement and the assumed loading used for magnetic-field modeling in the Petition must be accounted for.[7] National Grid data indicated that loadings on the S and T Cables during the time of measurement varied from approximately 20 to 65 MVA, well below the MVA loadings assumed for each line for calculation of magnetic fields in the Petition. The ratios of the recorded line loadings at the time of measurements to a full load of 250 MVA were used to scale down the modeled magnetic fields presented in the Petition to those expected at the time of the measurements.[8] These scaled-down values were then compared to the measured magnetic-field levels at the same loadings.

Figure 4 provides an example of the scaling computation described above for one of the twelve measurement locations. In this location, the line loading at the time of magnetic-field measurements was 39 MVA. The ratio of modeled load (250 MVA) to actual load at the time of measurement is calculated to be 6.4. The magnetic-field values presented in the Petition (71 mG above the cables and 24–26 mG ±25 feet from the centerline) are divided by 6.4,

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[7] Note that the current on the GCCs is of critical importance for a direct comparison of measurements to modeling, and measurements of these GCC currents were possible only at the Canal Street Switchyard and the Salem Harbor Substation (i.e., for the station side of Manholes 1 and 6—locations 1a and 6b). Direct comparisons of measurements to calculated values of the magnetic field for as-built conditions were not possible at the remaining manhole locations because there was no safe way to access the manholes to measure GCC currents without multiple outages of the S and T Cables.

[8] Scaling of the measured magnetic-field values up to 250 MVA was not regarded as accurate because of the imbalance between the loadings of the two lines and the likelihood of scaling up contributions to measured magnetic fields from unrelated sources.

resulting in scaled values of 11 mG over the cables and 3.8–4.1 mG ±25 feet from the centerline.

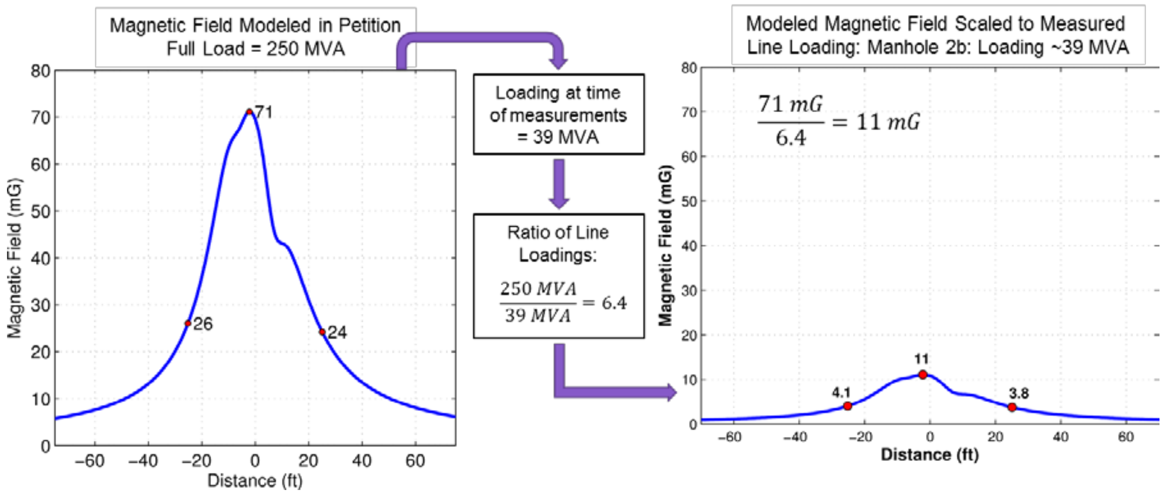

Figure 4. Example scaling of modeled magnetic field at 250 MVA load to that expected at a load of 39 MVA

Because there are differences in the physical configuration of every manhole approach (e.g., different lengths and different separation distances), this analysis was performed separately for each of the 12 measurement locations. In Figures 5a and 5b, the median magnetic-field levels at these 12 locations are compared to median scaled-down modeled values over the cables and ±25 feet from the centerline. In addition, the maximum and minimum values are shown above and below the median values. The results of this analysis for the maximum measured magnetic field[9] are shown in Figure 5a, while the results ±25 feet from the centerline are shown in Figure 5b.

9 The median distance from the duct bank centerline to the measured maximum magnetic-field level was 1.5 feet.

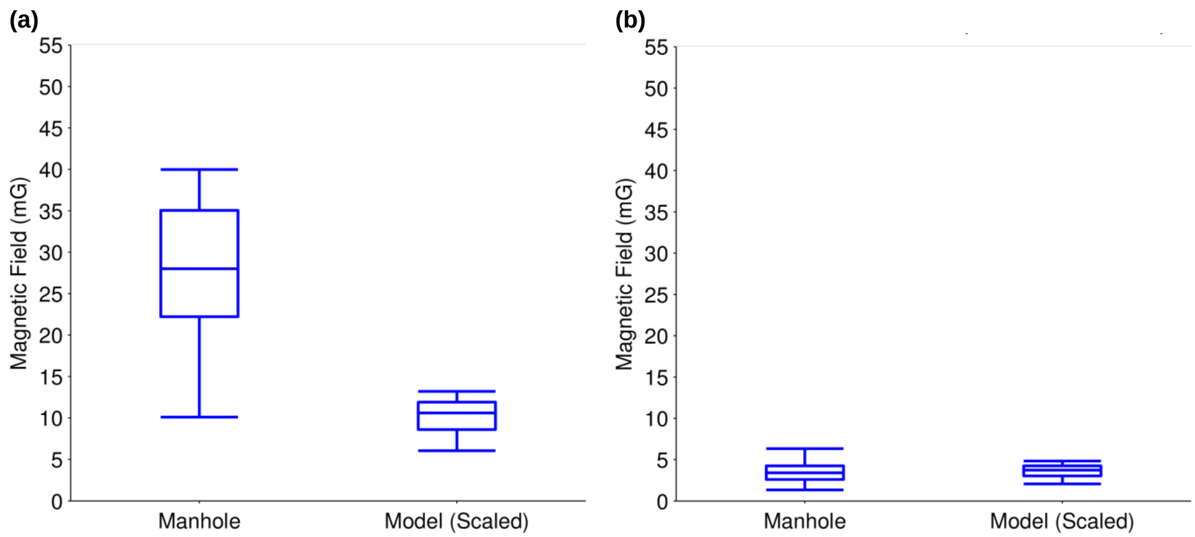

Figure 5. Measured magnetic-field levels at manhole entrances compared to values from the Petition scaled to the loading at the time of measurements: (a) maximum measured/modeled value; (b) measured/modeled value ±25 feet from the centerline.

The results of this analysis indicate that the maximum measured magnetic-field levels above the cables are approximately 2.5 times higher than those calculated based on the conceptual design and operational conditions in the Petition. At ±25 feet from the centerline, however, the results shown in Figure 5b indicate that the modeled and scaled values are quite similar but with a slightly greater spread. A summary of the results is presented in Appendix E, Table E-2. Since the magnetic field from the cables and the opposing magnetic field from the passive loop both vary in a linear fashion with load levels, the efficacy of the passive loops would be expected to be similar across a wide range of loadings up to 250 MVA.

A similar comparison of measured and modeled magnetic-field levels was also performed for the portions of the route where the underground lines were installed in the typical horizontal configuration (these locations are shown by the seven teal arrows in Figure 1) between manholes. Results of this analysis, presented in Figure 6, show that the measured magnetic fields, both over the duct bank and ±25 feet from the centerline, were similar to those values presented in the Petition when scaled to the loading at the time of measurements.[10] For both comparisons, the measurements exhibited a slightly greater spread in recorded levels than the corresponding modeling. A summary of the results is presented in Appendix E, Table E-3.

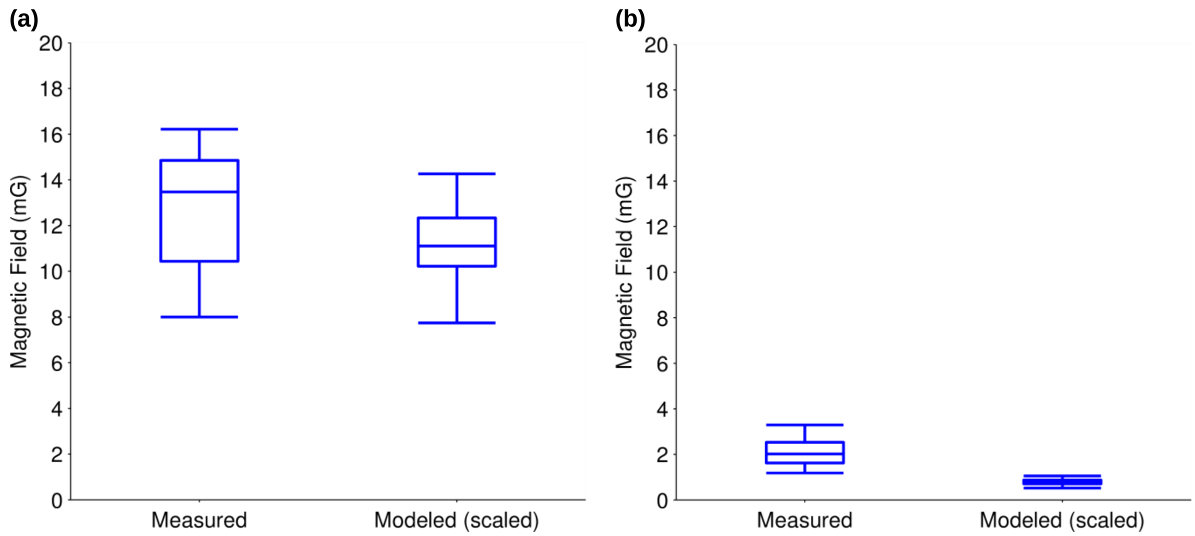

Figure 6. Measured magnetic-field levels over the horizontal duct bank configuration compared to values from Appendix 5-2 of the Petition scaled to the loading at the time of measurements: (a) maximum measured/modeled value; (b) measured/modeled value ±25 feet from the centerline.

[10] Note that measured magnetic-field levels ±25 feet from the centerline are sufficiently small that they likely include some contributions from other sources such as distribution lines or induced currents on adjacent infrastructure.

Discussion

As described above, the passive loops are effective in reducing magnetic-field levels around manhole duct banks, but the magnitude of the reduction in the magnetic fields was less than expected. The overall level of the measured magnetic field was higher than calculated over the manholes but not ±25 feet from the centerline of the duct banks. There are several reasons for these differences. Although the installation of the transmission lines and passive loops was generally consistent with the conceptual design modeled by Exponent in the Petition, variations between the conceptual design and assumed line loadings from the configuration of the lines and loading patterns in this project post-construction contribute to the observed differences in magnetic-field levels.

Differences between As-Built Configurations and Conceptual Model

- In the conceptual model, loadings on the two transmission lines were assumed to be equal; however, at the time of measurements the loadings of the two lines differed by ~10% (see Figure B-5a in Appendix B).
- In the conceptual model, currents on each of the three phase conductors of each line were assumed to be equal (balanced); however, the measured phase currents differed by ~10% (see Figure B-5b in Appendix B).
- The phase angles of the currents measured on the GCCs differed from those calculated and used in the conceptual modeling, likely due to unequal loading of the two lines, the current imbalance, and the presence of underground infrastructure elsewhere along the line.
- The manholes were modeled in the Petition as side by side with generic 50-foot-long rectangular passive loops on each side of the duct bank (symmetric). The as-built configuration of the transmission lines with one vault installed farther along the route than the other resulted in asymmetric

passive loops. The as-built passive loops varied from 15 to 60 feet in length and were often of irregular shape (see Figure B-6b in Appendix B).

- The phase conductors of one circuit were not installed in an ABC configuration above the second circuit in a CBA configuration but rather in two triangles (see Appendix B). This would produce no functional difference between these configurations if the currents on the phase conductors were all equal as applied in the conceptual model.

The above differences in the as-built configuration compared to the conceptual design contribute to the measured differences in magnetic-field levels. These differences were accounted for in post-construction modeling by using the as-built specifications and by modifying the original models to incorporate these noted differences (as was done in calculating the efficacy of the passive loops, as described above, and in further investigating the effect of these differences between the conceptual and as-built designs in Appendix D).

The implications of the above differences suggest that:

- Phase current balance can be a dominant factor in determining magnetic-field levels, especially for closely-spaced conductors of underground installations.
- The currents induced on GCCs of underground circuits can be affected in complex ways by multiple operational and non-design conditions.
- Consideration of the implementation of passive loops may be best evaluated in the latter stages of project design when likely as-built conditions are better known.
- Incorporation of mitigation systems more complex than optimal phasing requires more knowledge and control of unpredictable system operation than is currently available.

Mitigation Options

There are various methods for reducing magnetic-field levels from transmission lines, and National Grid incorporated several of these methods into the project design. The most effective options for reducing magnetic fields from transmission lines are to construct two lines together in the same duct bank with close phase-phase spacing and select the phasing of the lines in an arrangement for optimal mutual cancellation of magnetic fields.[11] These options were part of the design for the entire project route both above duct banks and at manholes. At manholes, where the two circuits separate to enter their individual manhole vaults, the separation between the circuits and the phase spacing among conductors increases. With this separation, the mutual cancellation of magnetic fields from individual conductors decreases, resulting in higher magnetic-field levels. At these locations, the addition of passive loops was selected in this project as an additional low-cost method of reducing magnetic-field levels. However, there are other options for potentially further reducing magnetic-field levels, including:

- capacitive compensation for the passive loops
- energizing the loops to make active loops
- metal plate shielding of the duct bank.

Each of these options is discussed in greater detail below.

Capacitive Compensation

As discussed above, the reactance of the passive loops can be reduced by adding, in series with the loop inductive reactance, compensation reactance in the form of series capacitance. This capacitance can decrease the overall impedance of the loop, thus increasing the flow of current in the loop to enhance the cancellation of magnetic fields generated by the transmission lines. Capacitive compensation was also considered in the Petition for the conceptual design evaluated

[11] A preliminary design involving a single transmission line at 250 MVA resulted in magnetic-field levels of approximately 250 mG directly above the duct bank compared to a dual-circuit duct bank in which the highest calculated level was 55 mG. Note that measurements above the dual-circuit duct bank showed similar values to those calculated (when adjusted for loading).

(Exponent 2013, p. 2). Additional analysis of the operational and logistical considerations for the installation of capacitive compensation has led to the following conclusions:

- The needed capacitance for compensation would require a bank of capacitors larger than the manholes.
- These capacitors would be electrolytic capacitors, which require ventilation and cannot be installed in manholes (even if the manholes were larger).
- The "tuning" of the passive loops by adding capacitors would require multiple and lengthy outages of both lines and simultaneous tuning of four passive loops at each of the six manholes.
- The capacitors would require periodic maintenance and line outages.

For the reasons discussed above (and others), capacitive compensation was not considered a viable option for further reducing magnetic-field levels at the manholes. A more extensive description of the functioning of capacitive compensation is included in Appendix F.

Active Loops

Another option for reducing magnetic-field levels is to inject electric currents into the passive loops, increasing the degree of cancellation of the magnetic field from the phase conductors, to create active loops, an option discussed in the Petition (Exponent 2013, p. 19). For the manholes under consideration here, this would require four separate active loops at each manhole. Active loops would require the following:

- excavating the street to place the four small antennas at the locations of interest to measure the magnetic field;
- connecting the small antennas and digital electronics within the manholes;
- providing low-voltage alternating power sources to drive the active loops (would require street excavation and distribution-class voltage sources);
- designing a feedback algorithm to minimize the measured magnetic field; and
- communicating between each pair of loops/algorithms.

Although the theoretical functioning of active loops has been demonstrated mathematically, Exponent is unaware of any active loops installed in any utility transmission system; this would therefore be a theoretical solution with no certainty of effectiveness. Active loops were therefore not considered a viable option for additional magnetic-field reduction at the manholes. A more extensive description of the functioning of active loops is included in Appendix F.

Shielding

Another option for reducing magnetic fields is shielding them with either ferromagnetic plates or layers of high conductivity materials such as copper and aluminum metal plates. These metal plates could be placed over the transmission lines at the manhole approaches to reduce magnetic-field levels above the shielding plates. Installation of the plates would have the following logistical considerations:

- excavation of the roads for installation;
- complex installation, including precision welding and grounding of the plates; and
- increased heating of the transmission cables due to the proximity of the metal plates leading to
    - a reduction in the cable ampacity, and
    - an increased cable degradation rate.

Additionally, while installing metal plates would likely decrease magnetic-field levels directly over the plates, it would likely increase magnetic fields at the edges of the plates and beyond. Installing shielding over the duct banks was therefore not considered a viable option for reducing magnetic-field levels at the manholes. A more in-depth discussion of shielding is included in Appendix F.

Discussion

Several mitigation options beyond installing passive loops have been discussed. Each has a fundamental flaw: uncertainty of effectiveness, unreasonable logistical requirements, or high costs (both financial and in time). None of these options is therefore considered viable for further reduction of magnetic fields from these lines. However, the analysis presented indicates that for this project the chosen methods of magnetic-field reduction (i.e., dual-circuit duct bank with optimally phased conductors) and the installation of passive loops represent viable low-cost or no-cost methods for reducing magnetic fields at the manhole approaches, consistent with the EFSB guidance.

Conclusions

In compliance with Condition M, the magnetic fields from the transmission line cables over the passive loops at each manhole were measured, and the results have been compared to information previously provided.

Where measurements of GCC current could be made (at the station side of Manholes 1 and 6), comparing measurements and modeling using the as-built geometry and loading indicates that the passive loops attenuate the peak magnetic field at manholes by approximately 20–27%. At ±25 feet, the passive loops have a weaker effect; however, measured magnetic fields are similar to or weaker than those modeled for manholes with passive loops.

Additional comparisons of measured magnetic fields to scaled Petition values indicate that the peak-measured magnetic field above the duct bank is approximately 2.5 times higher than that calculated for the conceptual design. At ±25 feet from the centerline, the measured magnetic-field levels are similar to those submitted in the Petition, with a lower measured median value but a higher spread and a higher maximum.

Magnetic-field levels are higher than modeled for the Petition, due to a variety of differences between the conceptual model and the as-built or as-operated duct banks. Differences include asymmetric passive loops, phase imbalance, unequal loading of the S and T Cables, and phase and magnitude shifts on the GCC currents.

Various other options have been considered for further reducing magnetic-field levels at the manhole approaches, including capacitive compensation of the passive loops, converting the passive loops to active loops, or installing shielding. An analysis of the feasibility, efficacy, and cost-effectiveness of these additional options does not support their use in further reducing magnetic-field levels in this project. The passive loops remain the most appropriate low-cost reduction option for this project.

Appendix A

Summary of Previous Magnetic-Field Calculations

Figures 7, 13, and 17 and Tables 1, 5, and 6 from the Exponent (2013) report (included as Appendix 5-2 to the Petition) are reproduced below for ease of reference.

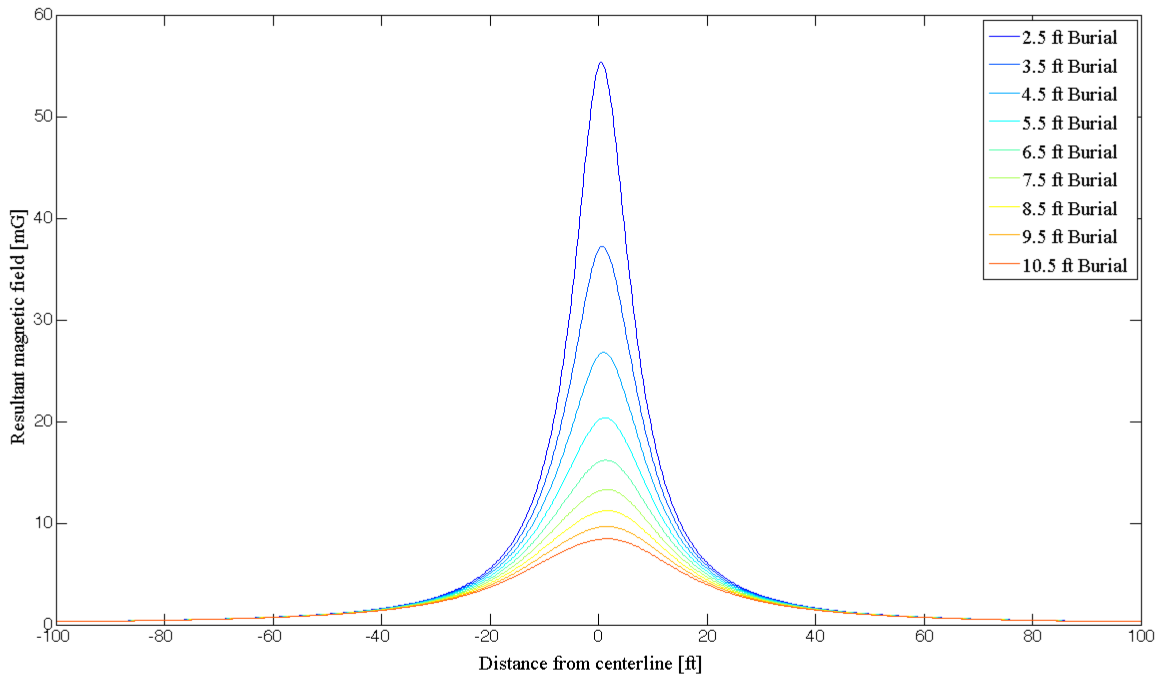

Figure A-1. Reproduction of Figure 7 from Appendix 5-2 to the Petition: Magnetic field (milligauss [mG]) for the horizontal duct bank configuration. Magnetic fields are calculated at a height of 3 feet above ground for various burial depths ranging from 2.5 to 10.5 feet.

Table A-1. Reproduction of Table 1 from Appendix 5-2 to the Petition: Magnetic field (mG) for the horizontal duct bank configuration

Burial Depth (feet)	Distance from duct-bank centerline (feet)												
	-100	**-75**	**-50**	**-25**	**15**	**10**	**MAX**	**10**	**15**	**25**	**50**	**75**	**100**
2.5	0	1	1	4	9	16	55	19	10	4	1	1	0
3.5	0	1	1	4	8	14	37	16	9	4	1	1	0
4.5	0	1	1	4	8	12	27	14	9	4	1	1	0
5.5	0	1	1	3	7	11	20	12	8	4	1	1	0
6.5	0	1	1	3	7	9	16	11	7	4	1	1	0
7.5	0	1	1	3	6	8	13	10	7	3	1	1	0
8.5	0	1	1	3	6	8	11	9	6	3	1	1	0
9.5	0	1	1	3	5	7	10	8	6	3	1	1	0
10.5	0	1	1	3	5	6	9	7	5	3	1	1	0

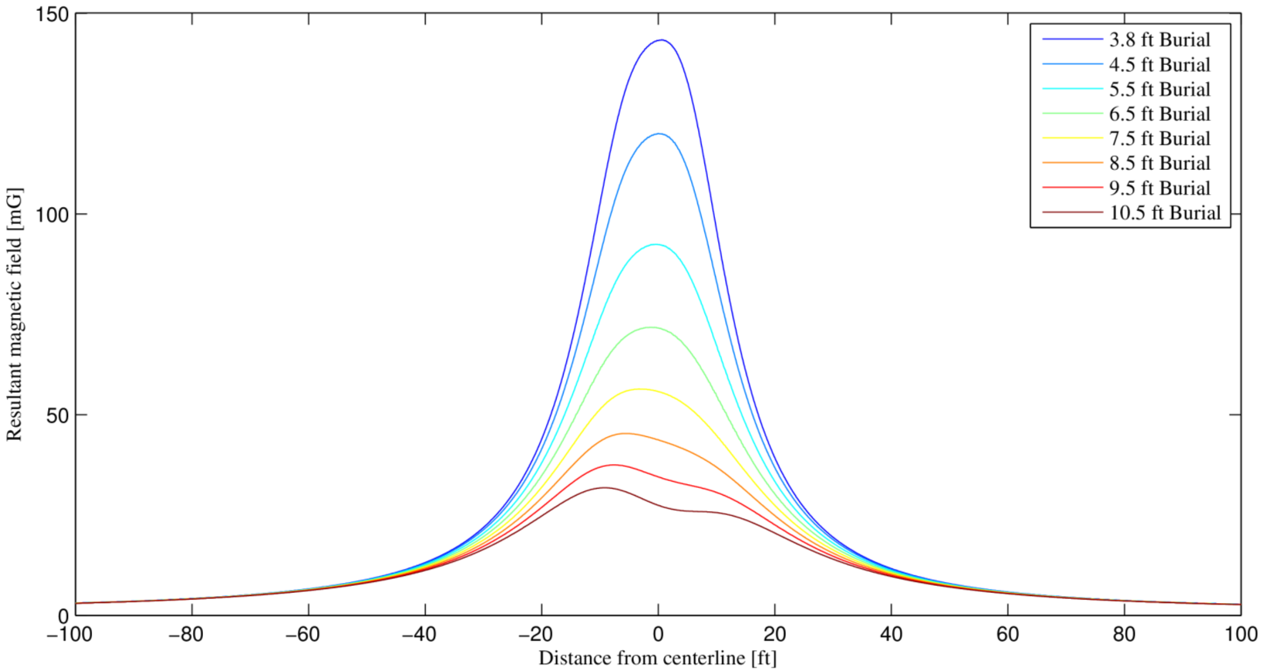

Figure A-2. Reproduction of Figure 13 from Appendix 5-2 to the Petition: Magnetic field (mG) for the manhole entrance configuration. Magnetic fields are calculated at a height of 3 feet above ground for various burial depths ranging from 3.8 to 10.5 feet.

Table A-2. Reproduction of Table 5 from Appendix 5-2 to the Petition: Magnetic field (mG) at a height of 3 feet above ground for various burial depths for the manhole entrance configuration.

Burial Depth (feet)	Distance from duct-bank centerline (feet)												
	-100	**-75**	**-50**	**-25**	**15**	**10**	**MAX**	**10**	**15**	**25**	**50**	**75**	**100**
3.8	3	5	9	30	67	103	143	96	61	27	8	4	3
4.5	3	5	9	29	62	90	120	83	55	26	8	4	3
5.5	3	5	9	27	54	74	92	67	48	24	8	4	3
6.5	3	5	9	26	47	61	72	55	41	22	8	4	3
7.5	3	5	9	24	42	51	56	45	36	21	7	4	3
8.5	3	5	8	23	37	43	45	37	31	20	7	4	3
9.5	3	5	8	22	33	37	37	31	27	18	7	4	3
10.5	3	5	8	20	29	32	32	26	24	17	7	4	3

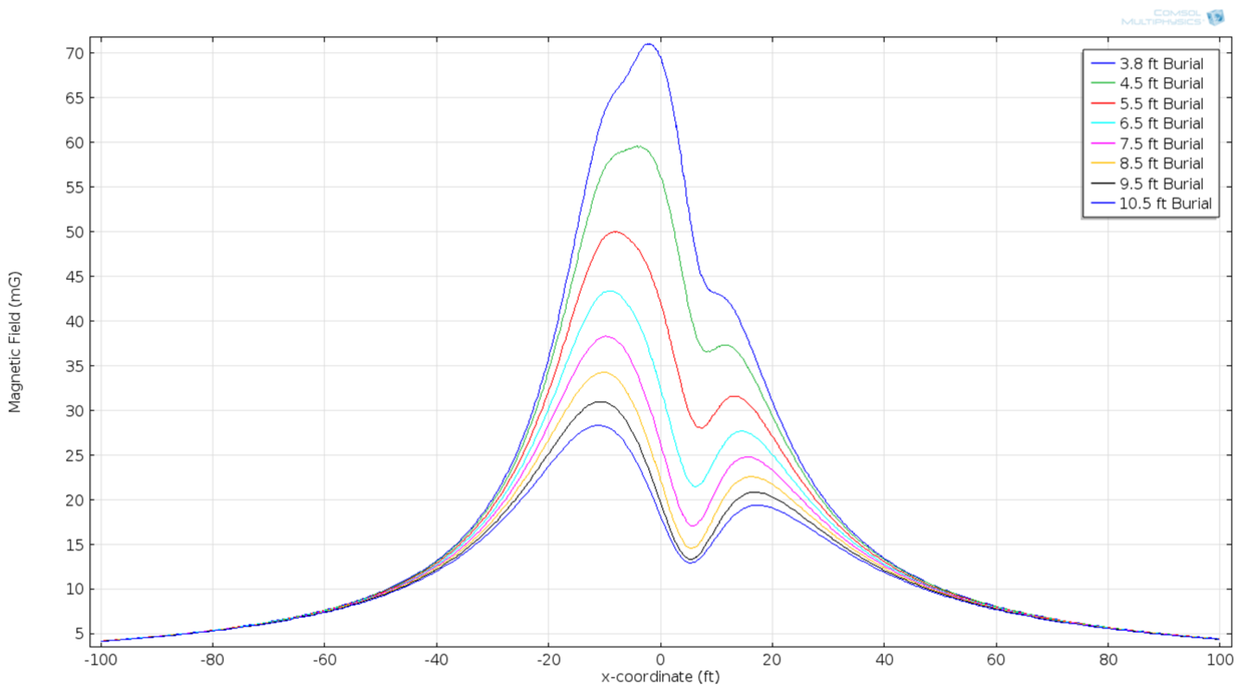

Figure A-3. Reproduction of Figure 17 from the Appendix 5-2 to Petition: Magnetic field (mG) for the manhole entrance configuration with uncompensated passive loops. Magnetic fields are calculated at a height of 3 feet above ground for various burial depths ranging from 3 feet, 10 inches to 10 feet, 6 inches with a passive loop 50 feet long and 6 feet high placed 9 inches outside of the phase conductors on each side of the duct bank.

Table A-3. Reproduction of Table 6 from the Appendix 5-2 to Petition: Magnetic field (mG) for the manhole entrance configuration with uncompensated passive loops

Burial Depth (feet)	Distance from duct-bank centerline (feet)												
	-100	**-75**	**-50**	**-25**	**15**	**10**	**Max**	**10**	**15**	**25**	**50**	**75**	**100**
3.8	4	6	10	26	50	63	71	43	39	24	10	6	4
4.5	4	6	10	25	46	57	60	37	36	24	10	6	4
5.5	4	6	10	24	42	49	50	30	31	23	10	6	4
6.5	4	6	9	23	38	43	43	24	28	21	10	6	4
7.5	4	6	9	22	35	38	38	21	25	20	10	6	4
8.5	4	6	9	22	32	34	34	18	22	19	10	6	4
9.5	4	6	9	21	29	31	31	17	21	19	10	6	4
10.5	4	6	9	20	27	28	28	16	19	18	10	6	4

Appendix B

Transmission Line Configurations

Manhole Approach and Passive Loop Configurations

The existing underground S and T Cables were replaced by a single underground dual-circuit concrete duct bank with 5,000 thousand circular mils (kcmil) enamel-coated copper cables and two 0.74-inch-diameter ground continuity conductors (GCC). For most of the route, the lines were installed in a horizontal duct bank configuration, as depicted in Figure B-1. At manhole approaches, however, the circuits transition to a vertical duct bank configuration, as shown in Figure B-2, and then diverge around the manhole. Overhead and profile views of the circuits as they approach a manhole are presented in Figure B-3 and Figure B-4, respectively. As the two circuits approach a manhole, they first roll to a vertical duct bank configuration and then diverge until the horizontal separation is 10 feet at the manhole entrance.[1] The vertical separation between conductors also increases, beginning at the manhole approach at 1 foot and increasing to 2 feet at the manhole entrance. The vertical distance from the top of the duct bank to the earth surface varies between manholes and along the approach to each manhole. This vertical distance varies from 2 feet, 6 inches to 7 feet, 9 inches, but is typically ~3 to 4 feet. As shown in Figure B-3, this manhole approach occurs over a distance of ~20 to 40 linear feet on either side of the manhole.

National Grid installed two uncompensated passive loops outside the vertical circuit configuration at each manhole approach. One loop was installed beside each vertical circuit on each side of the manhole, for a total of four passive loops at each of the six manhole locations. Each passive loop extends from its respective manhole to a point near where the two circuits separate. Since the two manholes at each site are offset, each pair of passive loops is asymmetric, as illustrated in Figure B-3. The shorter passive loops vary from ~15 to 30 feet in length, while the longer passive loops vary from ~40 to 60 feet in length. The horizontal separation between the passive loop and the conductors of its adjacent vertical circuit is ~9 inches. These passive loops are marked in red in the manhole approach figures below.

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[1] Construction constraints limited the maximum horizontal separation between circuits at manholes 2 and 3 to no more than approximately 4 to 5 feet.

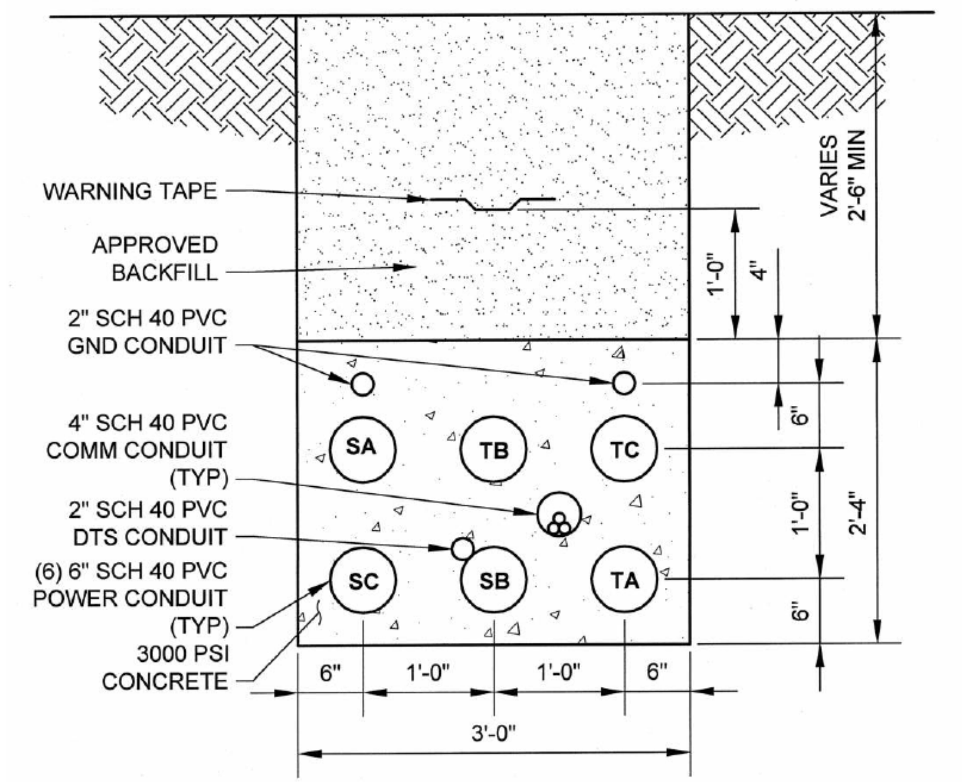


Figure B-1. Horizontal duct bank configuration. The SA, SB, and SC labels represent the A, B, and C conductors of the S Cable. Similarly, the TA, TB, and TC labels represent the A, B, and C conductors of the T Cable.

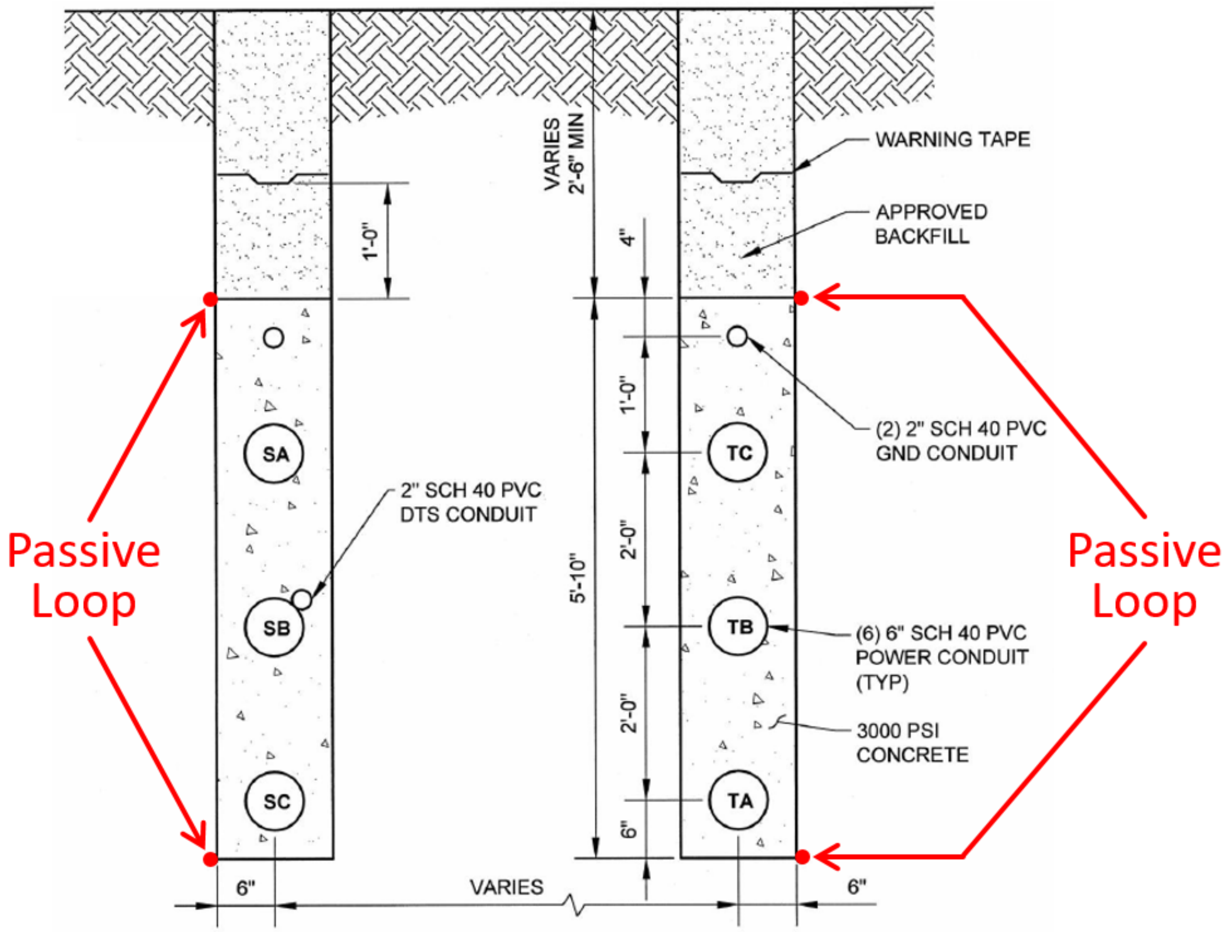


Figure B-2. Typical vertical duct bank configuration approaching a manhole entrance. The SA, SB, and SC labels represent the A, B, and C conductors of the S Cable. Similarly, the TA, TB, and TC labels represent the A, B, and C conductors of the T Cable.

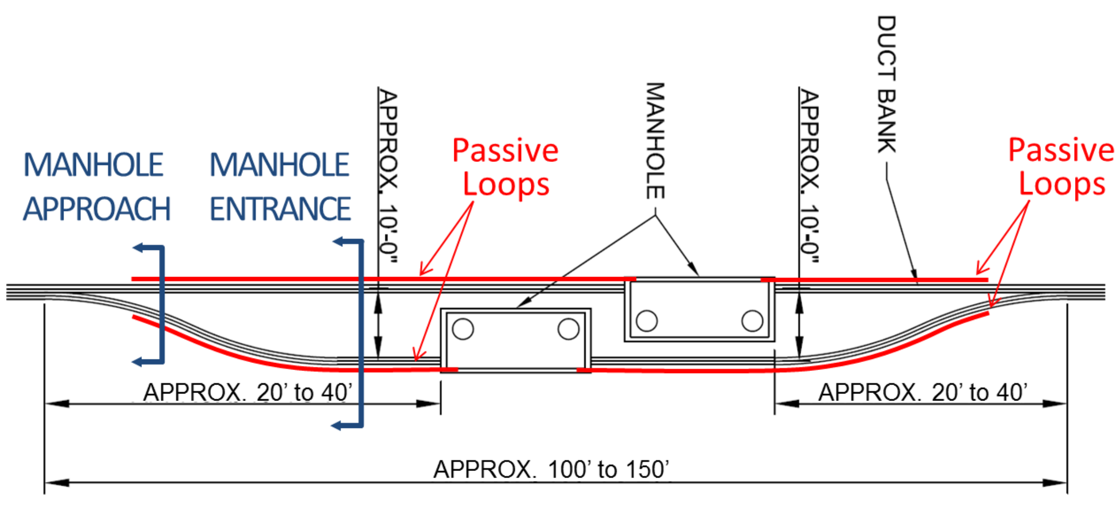


Figure B-3. Overhead view of a typical manhole approach

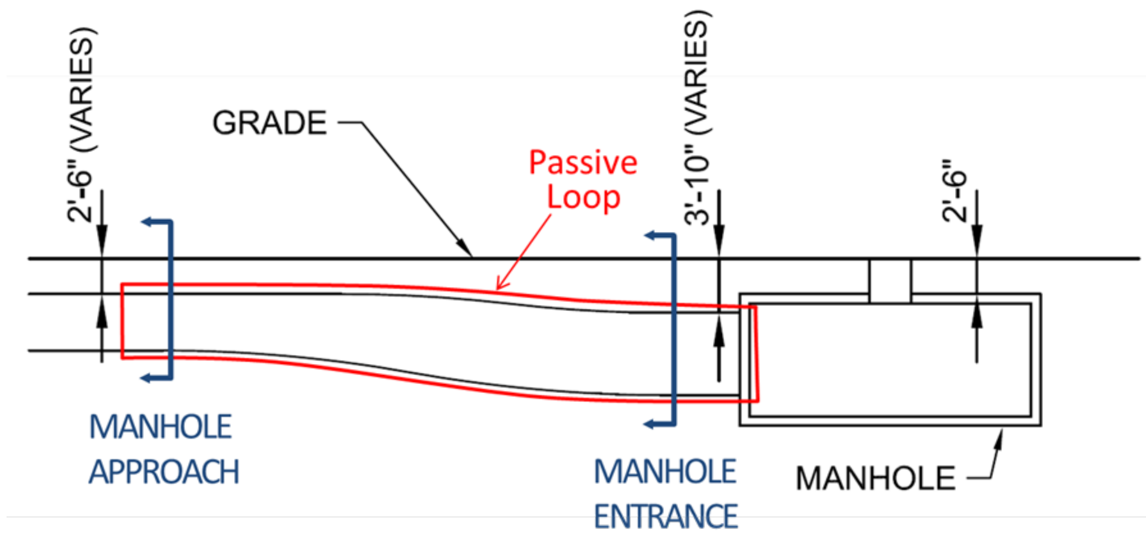


Figure B-4. Profile view of a typical manhole approach

Differences between As-Built Configurations and Conceptual Design

The report described the ways in which the as-built transmission line configurations differ from the conceptual design analyzed in Appendix 5-2 to the Petition. Measured loading on the transmission line conductors post-construction also differed from the balanced loading assumed in Appendix 5-2 to the Petition, and the asymmetric as-built passive loop installation also differed from the symmetric conceptual design. These electrical and physical differences are detailed below.

Electrical

In the conceptual design, a representative load of 250 megavolt-amperes (MVA) was assumed for each transmission line, the loadings on the two transmission lines were assumed to be equal and balanced, and the induced currents on each GCC were calculated assuming these balanced loadings. As the horizontal transmission line configuration comprises most of the project route, it was considered the determining factor in calculating level and phase of the currents induced in the GCCs. In the as-built configurations at the time of measurements, the loading varied from ~20 to 65 MVA. An example of the typical measured loadings of the phase conductors during post-construction measurements is shown in Figure B-5, with S Cable loading shown on the top plot and T Cable loading shown on the bottom plot. The loading of the A, B, and C phase conductors is shown in blue, green, and red, respectively, for each of the two transmission lines. Comparisons between the top and bottom plots in Figure B-5 show that the loadings on the S and T Cables differ by ~10%. In addition, Figure B-5 shows that the amplitude of currents on the individual phase conductors making up each line differs by ~10%. The current on each GCC also was measured post-construction. While the measured GCC current was similar in amplitude to that predicted by our computational modeling, phase angles of the measured currents differed from the calculated phase angles by up to ~18°. These unbalanced loadings and phase shifts to the GCC currents have a significant effect on the calculated magnetic-field levels near each manhole approach. Details regarding the measurement of GCC currents and phase angles are provided in Appendix C.

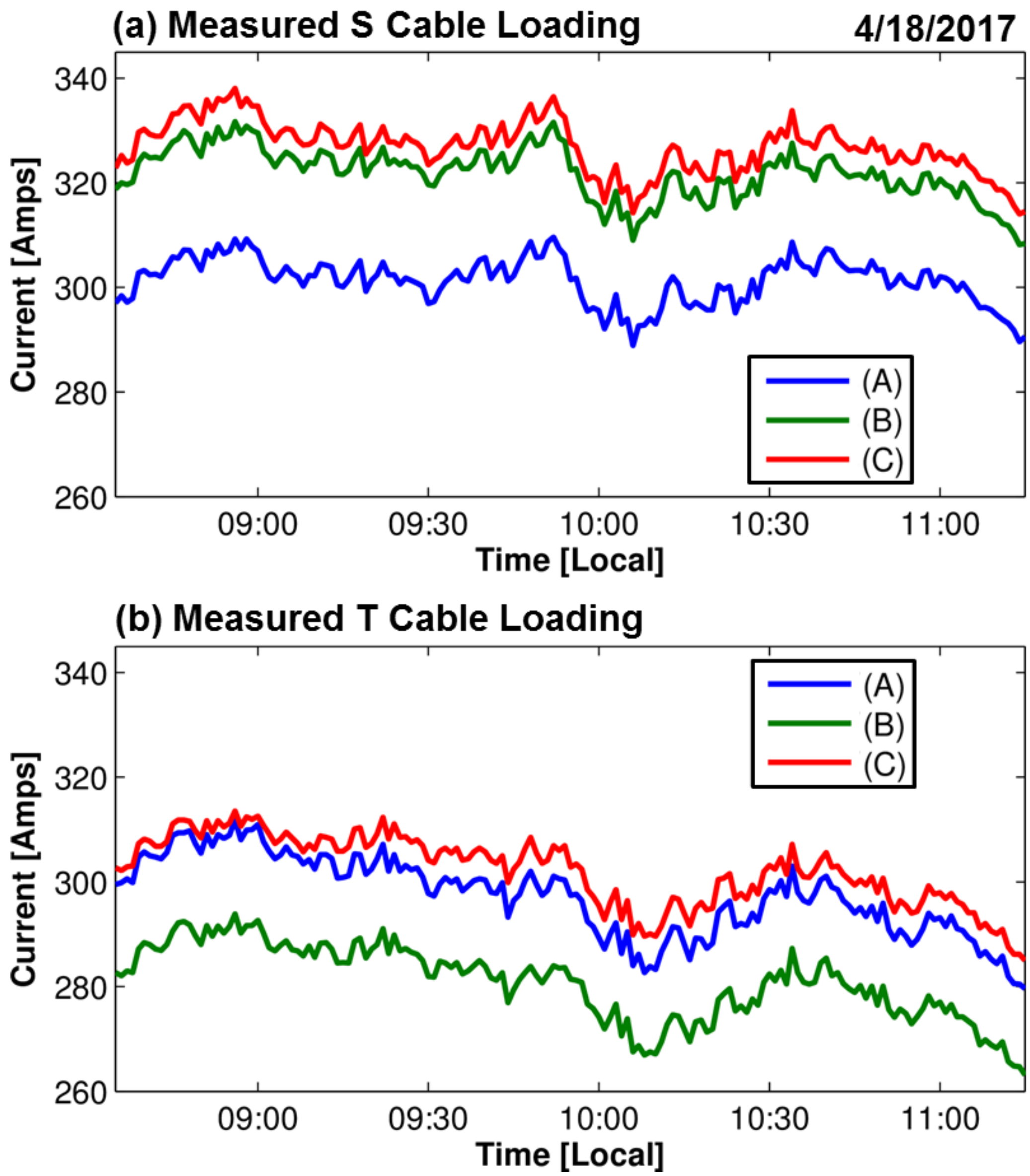


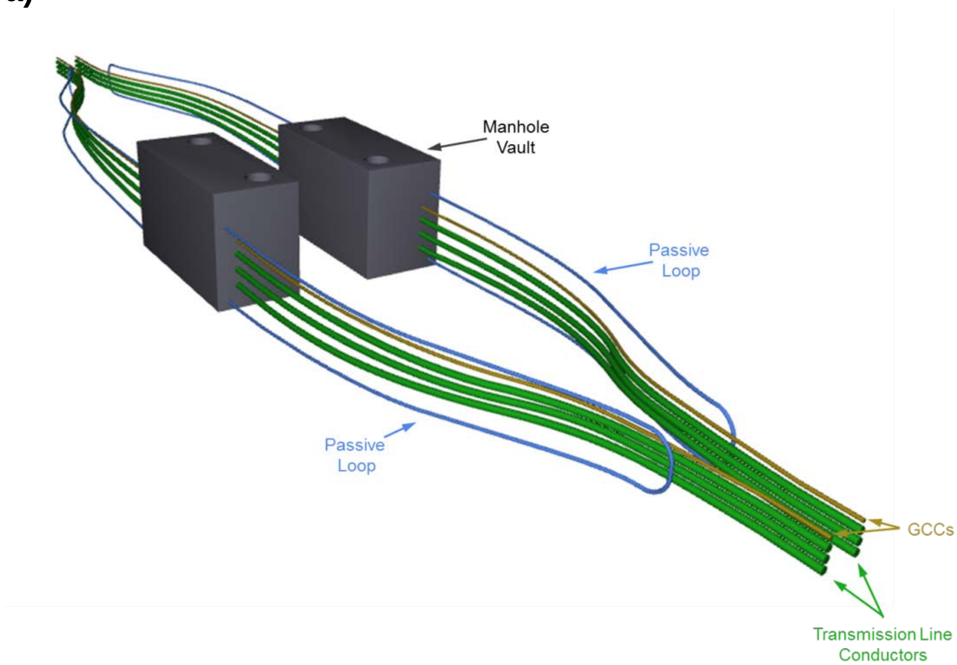
Figure B-5. Example of measured loadings on individual phase conductors A, B, and C as a function of time on each phase conductor for (a) the S Cable and (b) the T Cable Data recorded on April 18, 2017.

Physical

The conceptual design assumed generic, 50-foot-long rectangular passive loops located on each side of the duct bank along the approaches to each manhole. To analyze the location where the distance between transmission line conductors was at its highest, pre-construction analysis based this symmetric passive loop geometry off the manhole entrance configuration (see Figure B-2), where the horizontal distance between the transmission lines was assumed to be 10 feet. An illustration of this symmetric passive loop configuration is shown in Figure B-6a. Since the constructed manholes were offset along the transmission line path, each pair of as-built passive loops is asymmetric as illustrated in Figure B-6b. In these asymmetric as-built configurations, the shorter passive loops vary from ~15 to 30 feet in length, while the longer passive loops vary from ~40 to 60 feet in length. While the as-built passive loops are still approximately rectangular, they are each slightly irregular in shape, typically curving apart and increasing in height and burial depth as they approach the manhole entrance. As opposed to a constant horizontal separation distance of 10 feet between the transmission lines, this distance typically increased from 5 feet to 10 feet along the manhole approach. At some manholes, this separation distance was limited to no more than ~4 to 5 feet along the entire approach. Additional views of the typical as-built passive loop geometry are shown in Figure B-3 and Figure B-4.

In addition to the physical geometry differences discussed above, there was also a difference between the phasing of the conceptual line design and the phasing of as-built designs for the horizontal transmission line configuration. In the conceptual design for the horizontal configuration, one of the circuits was in a horizontal ABC phase configuration above the second circuit in a horizontal CBA configuration. In these as-built horizontal configurations, however, the phase conductors were installed in two triangles to make a shorter transition distance at the manholes when the circuits rolled to a vertical configuration. These conceptual and as-built phase configurations are illustrated in Figure B-7. Since the S and T Cables were assigned equal loading between lines and balanced loading between phases in the conceptual design, the conceptual phasing and the as-built phasing are functionally equivalent, and were calculated to produce identical magnetic-field levels. When the loadings are unequal or unbalanced, however, as in the operation of the lines in the as-built configuration, the two configurations lead to different magnetic-field levels. This change to the phase configuration was accounted for in our analysis of the electrical differences discussed above.

a)



b)

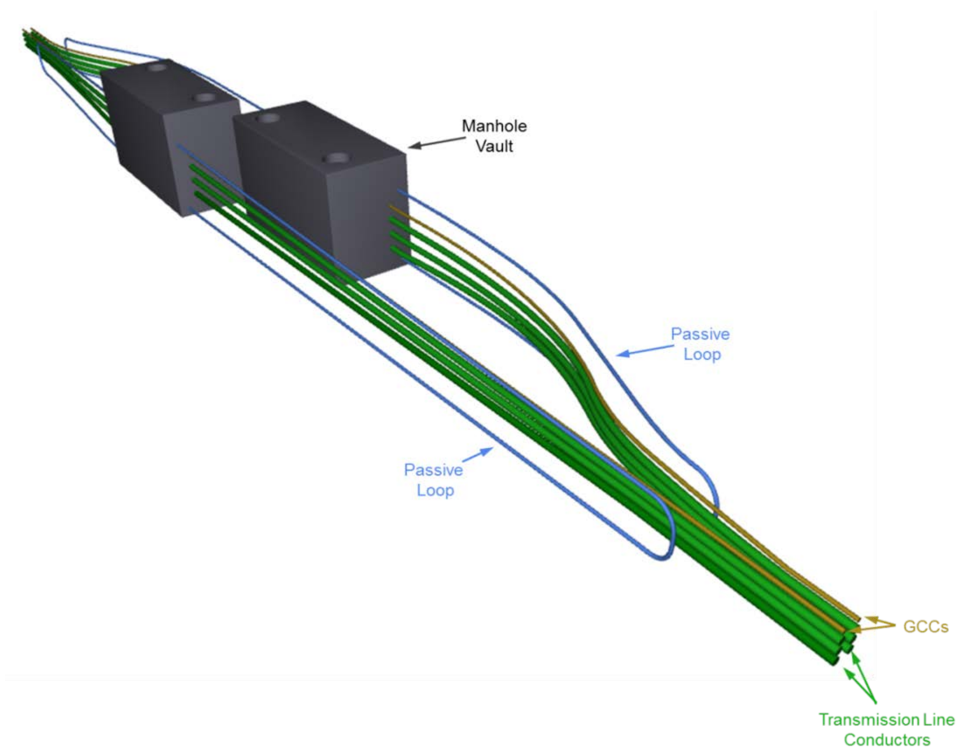


Figure B-6. Illustration of model for (a) symmetric passive loops used in Appendix 5-2 to the Petition and (b) asymmetric passive loops installed at manhole entrances

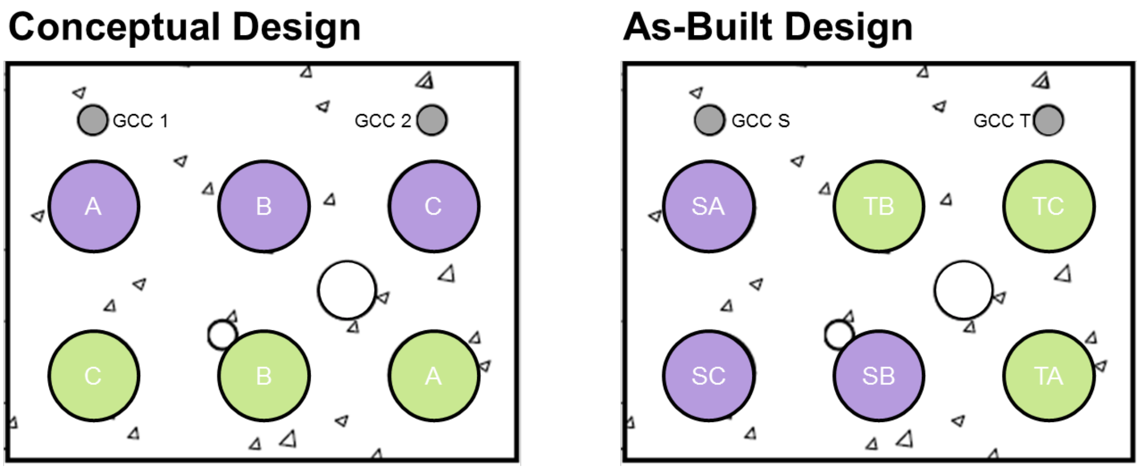


Figure B-7. Phasing of conductors in conceptual vs. as-built design. In these figures, the SA, SB, and SC labels represent the A, B, and C conductors of the S Cable. Similarly, the TA, TB, and TC labels represent the A, B, and C conductors of the T Cable.

Appendix C

Measurements

Measurement Locations

Magnetic-field measurements were made at 19 separate locations along the route of the transmission line between the Canal Street Switchyard and the Salem Harbor Substation. The measurements made at these locations and those reported elsewhere in this report were performed in accordance with standard instruments and procedures applicable to the measurement objectives.[1] At each location, Exponent performed measurements starting on one side of the duct bank, proceeding across the duct bank to the other side along a transect at least 25 feet to either side of the duct bank centerline (farther where accessible).

A schematic indicating the location of each measurement is shown in the body of this report in Figure 1 and a corresponding aerial photograph showing the location of each measurement transect is shown below in Figure C-1.

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.

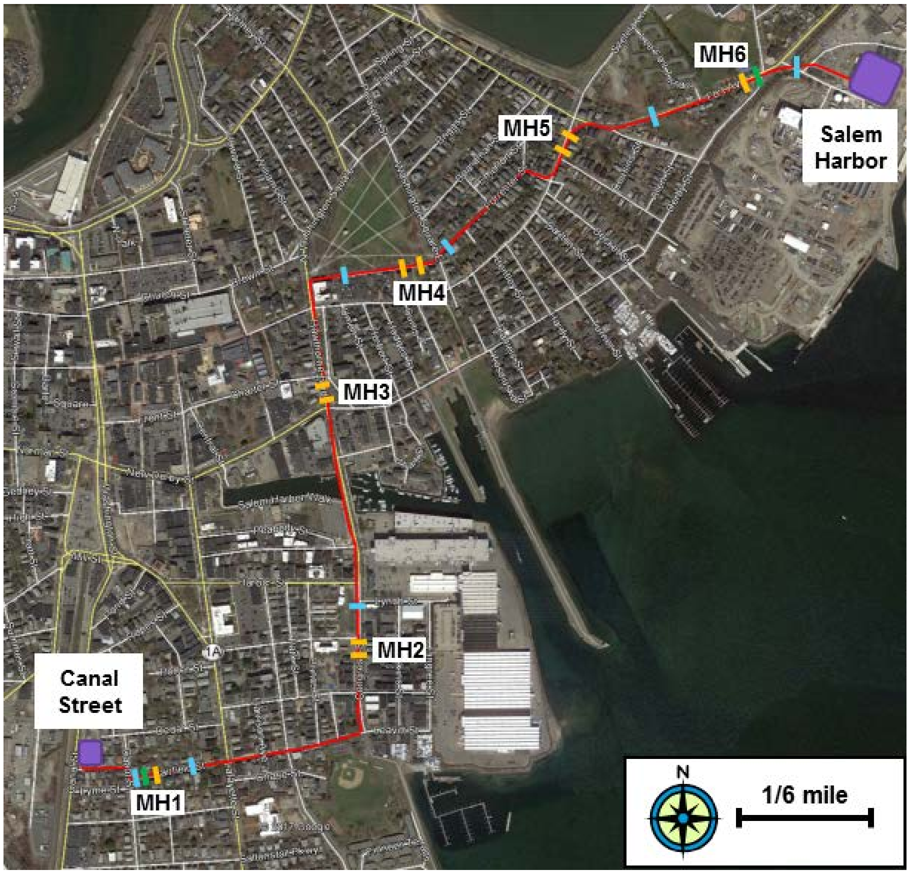


Figure C-1. Aerial view of transmission line route including terminus points, manhole locations and measurement transects. The color of measurement transects corresponds to those used in Figure 1 in the body of the report.

As in Figure 1, in the body of the report, the color of the measurement transects describes the location and type of measurement performed. Measurements to assess the efficacy of the passive loop were performed at the manholes closest to the substations (i.e., the Canal Street side of Manhole 1 and the Salem Harbor side of Manhole 6), the only locations where the ground continuity conductors (GCCs) are safely accessible without requiring multiple outages (GCC measurements are discussed in greater detail below). These locations are designated 1a and 6b, respectively, and are shown by green lines in Figure C-1. Additional measurements were taken at manhole entrances (two measurements each) to compare to the values provided in the Petition as shown by the yellow lines in Figure C-1. Finally, measurements were made over portions of the route installed in the "typical" horizontal configuration between each set of manholes at locations indicated by the teal colored lines.

Measurement Instruments

All magnetic-field measurements were made using the same equipment, though the methodology for the measurements differed among locations. At each location the magnetic field was measured in units of milligauss (mG) by orthogonally-mounted sensing coils whose output was recorded by a digital meter (EMDEX II, Entertech Consultants) and position was recorded either through use of a survey wheel or a measuring tape as discussed in greater detail below. A second magnetic-field meter (EMDEX LITE, Entertech Consultants) was placed on the ground above one of the transmission lines and set to continuously record fluctuations in the magnetic field caused by changes in current flow on the lines. These data were used to evaluate if there was a large change in loading during the time that measurements were taken.

These measurement meters meet the IEEE instrumentation standard for obtaining accurate field measurements at power line frequencies (IEEE Std.1308-1994) and were calibrated by the firm EMDEX, LLC, using methods like those described in IEEE Std. 644-1994 (R2008) and IEEE Std. C95.3.1-2010. The time and date of the field measurements were noted so that the loading on both of the lines at the time of field measurements could be matched to loading levels recorded by National Grid. Finally, a Kestrel 4000 weather meter (Nielsen-Kellerman Company) was used to record temperature, relative humidity, barometric pressure, and wind speed for reference as checks on official weather reports. A certificate of conformity for the meter is included in Appendix G.

Measurements to Assess the Efficacy of the Passive Loops

Assessing the efficacy of the passive loops requires knowing the position of each conductor approaching the manhole as well as the loading on each conductor at the time of measurements. The location of each conductor was identified from the as-built drawings produced during construction, and the loading of the transmission lines was provided by National Grid's telemetry monitoring of the S and T Cables at the Salem Harbor Substation. The current on the GCCs is induced in the cables due to their proximity to the transmission lines but is not similarly monitored by National Grid. In addition, the GCCs are grounded at each manhole as well as at the Salem Harbor Substation and Canal Street Switchyard, which means the current flowing on the GCC conductors will differ between each set of manholes (e.g., the current on the GCCs between Manhole 1 and Manhole 2 will differ from the current on the GCCs between Manhole 2 and Manhole 3, etc.). The only locations where the GCC currents could safely be measured without requiring multiple outages of both transmission lines was where the GCCs come up from underground inside the Salem Harbor Substation and the Canal Street Switchyard. Therefore, the only two locations where the efficacy of passive loops was assessed was between the Canal Street Switchyard and Manhole 1 (Location 1a) and between Manhole 6 and the Salem Harbor Substation (Location 6b). The measured magnetic fields at these locations were compared to calculated magnetic-field values for the measured phase and GCC currents and as-built conditions at these manhole locations.

Measurements of Ground Continuity Conductor Currents

The GCC currents were measured using a pair of Fluke 435 Power Quality Analyzers (PQAs) (Fluke Corporation). One PQA was connected to make measurements of the S transmission line, and the second was connected to make measurements of the T Cable. The calibration certificates for both these units (as well as the current probes) are included in Appendix G. The Fluke 435 PQA simultaneously records the amplitude and phase of current from three input channels. The PQA was used to measure the current on two of the transmission line phase conductors and on the GCC. The fourth input (typically used in power quality studies for the neutral conductor) did not record phase resolved measurements and so was connected to one of the sheath currents for reference. A photograph of the measurement setup for the PQA recording the T Cable currents at the Salem Harbor Substation is shown in Figure C-2, and an illustrative example showing the current connections is shown in Figure C-3. Also shown in this figure are the recording parameters used by the PQA. The PQA was set to record root mean square (RMS) and peak current amplitudes as well as the phase of the current of each input channel at 30-second sampling intervals.

To confirm the accuracy of the recorded PQA currents, Exponent compared the current amplitudes recorded by the PQAs to those recorded by National Grid. One such comparison is shown in Figure C-4. The example shown depicts the recorded S Cable currents measured at the Canal Street Switchyard from approximately 8:30 am to 11:30 am on April 18, 2017. Each sub-plot shows the variation in the magnitude of the measured current with time. The currents measured on the A-phase and B-phase conductors by the PQA matched the recorded National Grid measurements of phase currents to within approximately 5% or less. The figure also shows that the magnitude of the GCC current closely tracks the magnitudes of the phase currents as expected. Note that while the phase currents were measured as approximately 300–340 Amperes (A) during the time of recordings, the measured GCC current was far smaller, approximately 42 A.

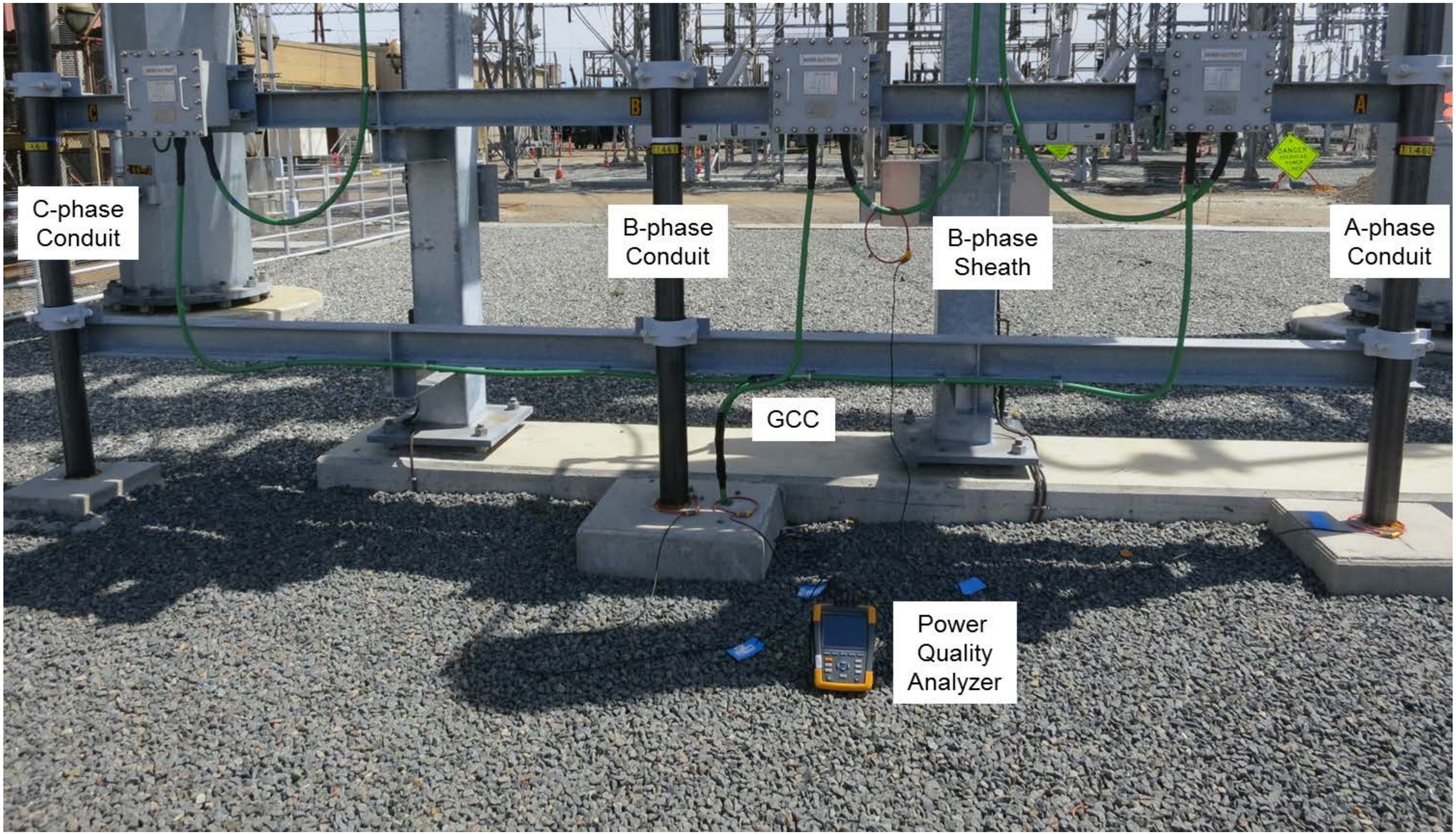


Figure C-2. Photograph of PQA measurements of the T Cable at the Salem Harbor Substation. Measurements made concurrently with magnetic-field measurements at Location 6b.

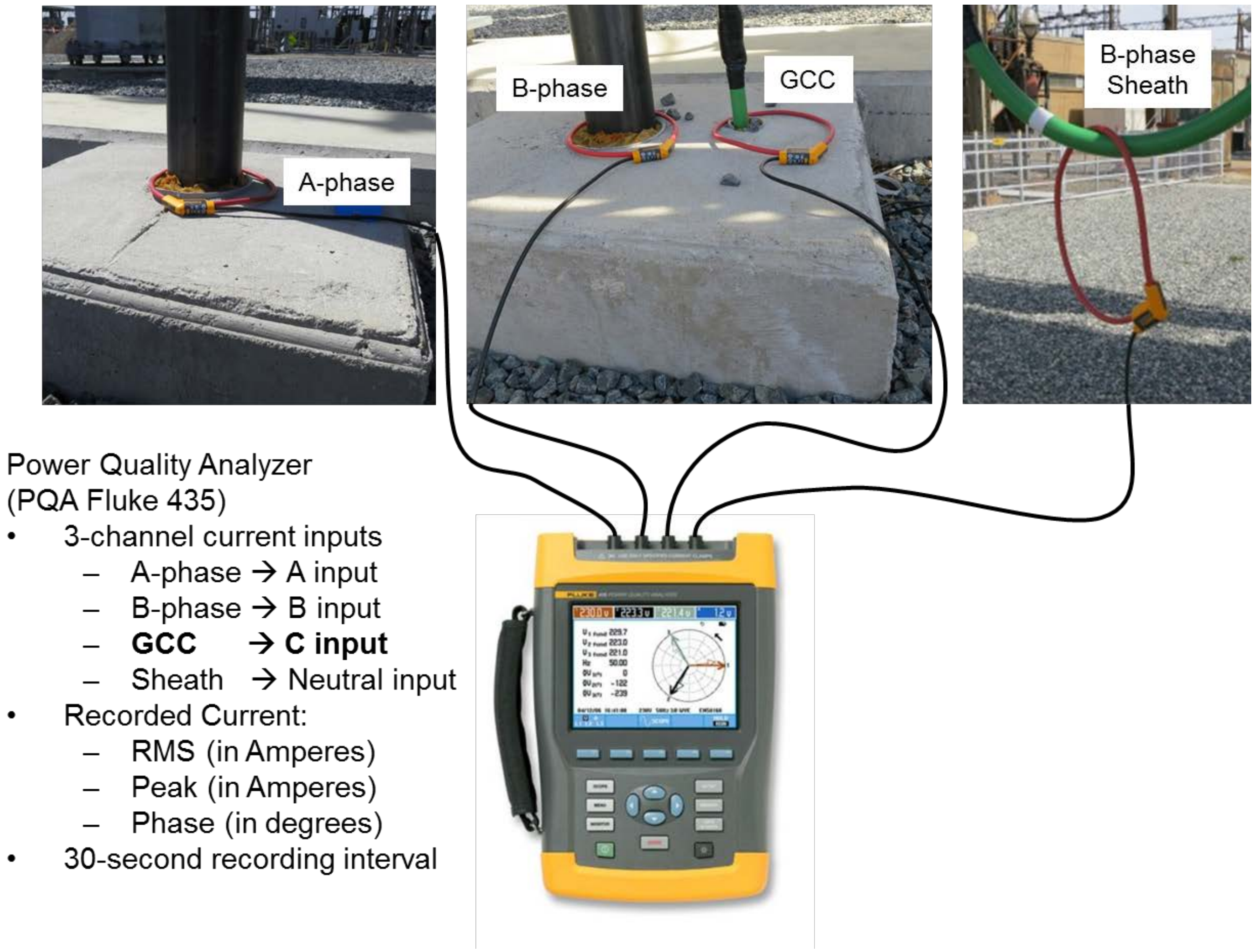


Figure C-3. Illustration showing the configuration of inputs used for the PQA measurements of the T Cable at the Salem Harbor Substation.

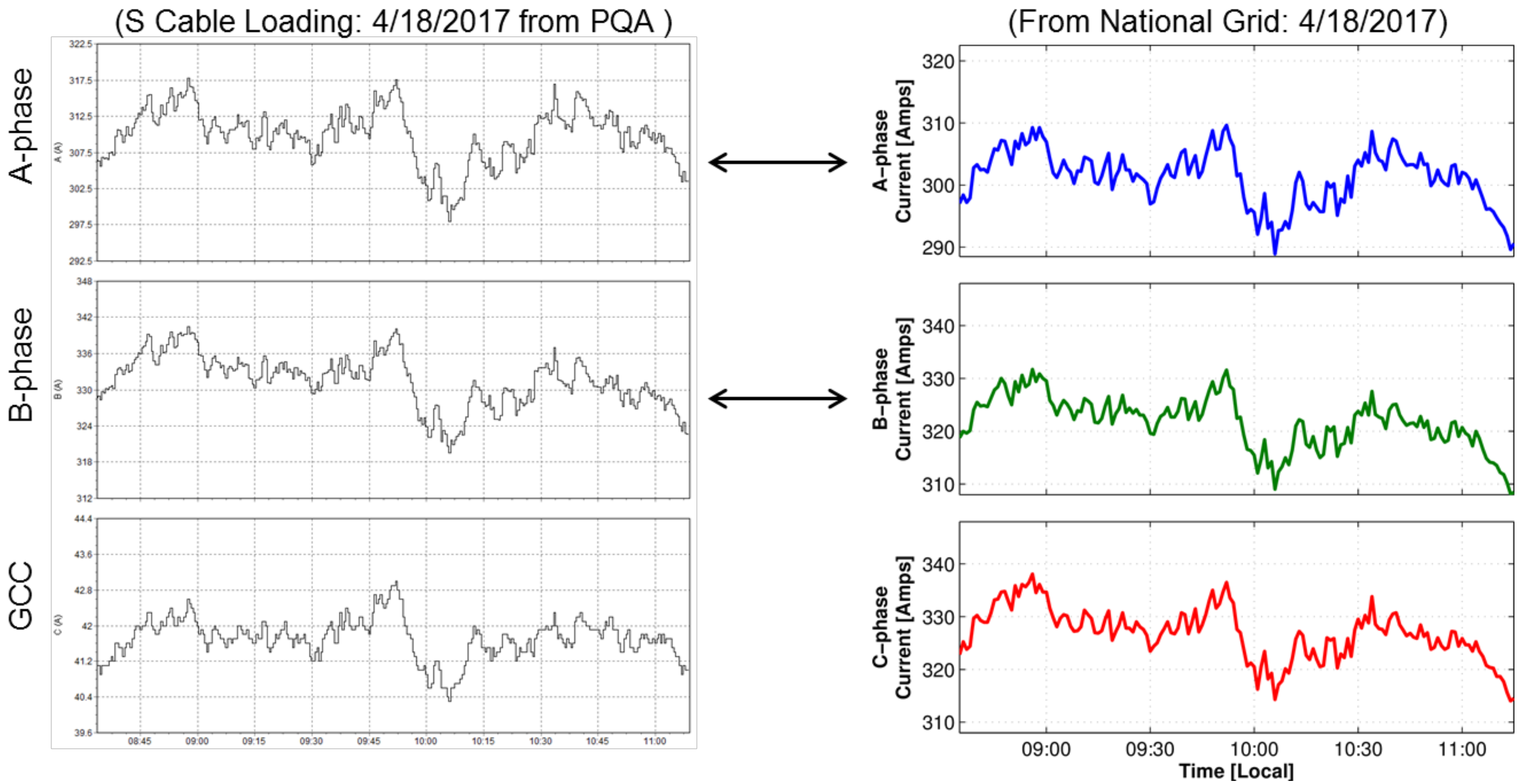


Figure C-4. Comparison of current measurements of the S Cable to those recorded by National Grid from approximately 8:45 am to 11:30 am on April 18, 2017. The S Cable (and GCC) measurements with the PQA recorded at the Canal Street Switchyard.

High Spatial Resolution Magnetic-Field Measurement at Locations 1a and 6b

Magnetic-field measurements at Location 1a (on the Canal Street Switchyard side of Manhole 1) were performed on April 18, 2017, between the hours of 9:30 am and 11 am. Measurements at Location 6b were performed on April 19, 2017, between the hours of 11 am and 12:15 pm. Before measuring the magnetic fields, the two PQA units were configured as described above and connected to measure the loading on both the S and T Cables (including both GCC currents) at the respective substations. At the manhole, Exponent engineers laid a long measuring tape on the ground across the center of the manhole approach (i.e., the middle of the passive loops) across the transmission line duct bank and secured it in place. At these two locations it was determined that high spatial resolution of the magnetic fields would likely be needed to make the most accurate comparison possible to modeling, and so measurements were performed at 3 inches to 1 foot spacing across the manhole approach (smaller spacing near the transmission lines and larger spacing at greater distances). Magnetic-field measurements were performed with two separate EMDEX II units: one at a height of 1 m above ground and the other at a height of 6 inches above ground. Both EMDEX II measurement units were configured to record the x, y, and z components of the magnetic field and to calculate the resultant field from those measurements. Comparisons of these measurements with the results of modeling are presented in Appendix D.[1]

Magnetic-Field Measurements at Manhole Entrances

Magnetic-field measurements at manhole entrances were performed shortly after the energization of the transmission lines, between July 5 and July 7, 2016. These measurements were each performed at a height of 1 meter above ground and extended along a transect at least 25 feet to either side of the duct bank centerline (and farther where accessible). High spatial resolution measurements were deemed unnecessary for these measurements and so the distance from duct bank centerline was acquired by attaching the EMDEX II magnetic sensor to a survey wheel and recording magnetic-field levels and distances simultaneously. The EMDEX II was configured to record the

[1] The measurements over the typical horizontal configurations followed the same measurement methodology.

x, y, and z components of the magnetic field and to calculate the resultant field from those measurements. For best comparison with modeling from Appendix 5-2 of the Petition, these measurements were performed at the entrance to the manhole (as opposed to the center of the passive loops). Current flows on the lines were recorded by National Grid during the measurements and were used to scale the modeling results provided in Appendix 5-2 of the Petition to the loading at the time of measurements as discussed in greater detail in Appendix E.

Appendix D

Modeling

Modeling Methods

Exponent calculated the magnetic-field levels above ground for as-built manhole approach configurations using three-dimensional (3D) finite element analysis in COMSOL Multiphysics (version 5.3). The simulation used the magnetic-field physics interface of COMSOL to solve the time-harmonic Maxwell-Ampere's law for the magnetic fields generated by the transmission line and GCC currents in the presence of the nearby passive loops. Each simulation included the as-built geometry for a single manhole approach including two passive loops as shown in Figure D-1.

The inputs to the simulations were the conductor geometry, material properties, and transmission line and GCC currents, and the outputs were the magnetic-field levels throughout the simulated domain. Transmission line and GCC currents were modeled as known line currents based on loading data recorded at the time of measurements.[1] The passive loops were each modeled as copper with a cross-sectional area of 1.0 square-inch (1,273 kcmil [thousands of circular mils]) and geometry based on as-built specifications. All background materials (e.g., concrete, earth, air) were treated as low-conductivity and with a relative permeability of 1.0. An infinite element domain was implemented around the circumference of the simulated region to effectively treat any domain boundaries as being infinitely far away. The end caps of the cylindrical model domain were assigned a magnetic insulation boundary condition to complete the circuit for the imposed line currents with minimal effect on the calculated magnetic fields and induced currents. Since most magnetic-field lines will circumscribe the transmission lines, the component of the magnetic-field vector normal to the end caps of the cylindrical domain will be small, and thus the effect of these boundaries on the calculated magnetic fields and induced currents will be negligible. For direct comparison to measurements, magnetic-field levels were calculated with high resolution (less than 6-inch spacing) along a transect at 1 m

[1] In pre-construction analysis, and for the investigation of select design differences discussed below, a 2D model to calculate the induced GCC currents preceded the 3D model described here. The 2D model utilized design specifications for the horizontal configuration and phase current loading values to calculate the induced currents on each GCC. These calculated GCC currents served as inputs to the full 3D model in cases where the GCC currents were not directly measurable.

above ground at a location midway along the manhole approach to coincide with the location of each measurement transect.

A wireframe view of the 3D-modeled geometry for a manhole approach including passive loops is presented in Figure D-1. The geometry shown here is based on as-built specifications for the Canal Street side of Manhole 1 (Measurement Location 1a). Proceeding from right to left in each view of Figure D-1, the two sets of transmission lines diverge in both the transverse and vertical directions as they approach the manhole vaults. The manhole vaults themselves are not physically represented in the modeled geometry. Each passive loop runs parallel to its adjacent transmission lines at a horizontal distance of 9 inches outside the transmission lines. For this illustrated approach to Manhole 1, the two passive loops are approximately 60 feet and 26.5 feet in length. The height of the longer passive loop varies from approximately 3 feet 7 inches to 7 feet 0 inches, while the shorter passive loop is approximately 6 feet 10 inches in height along its entire length.

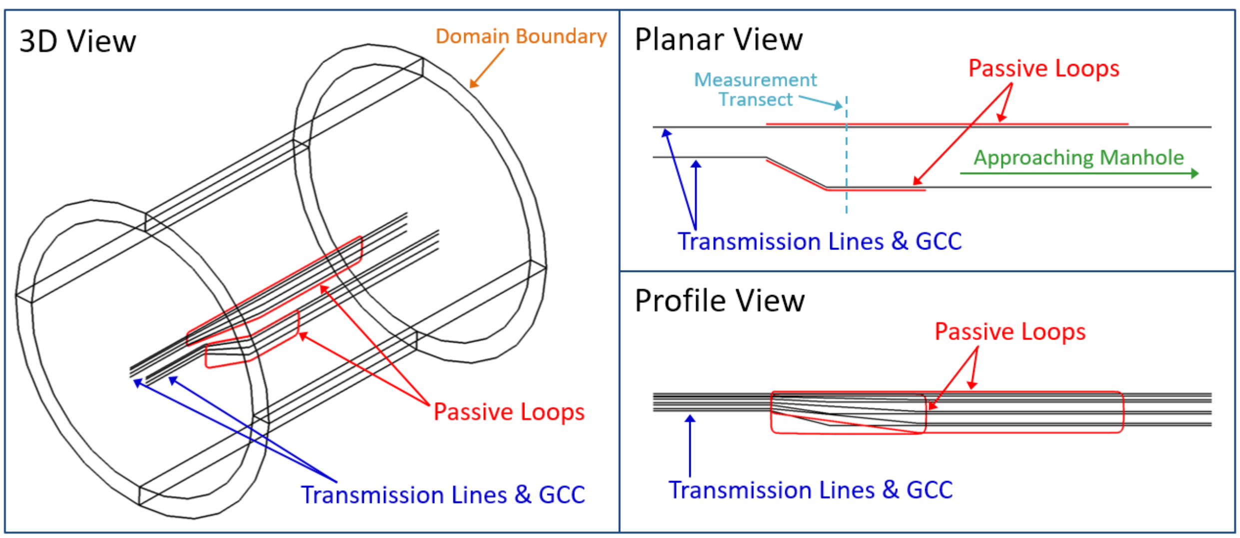


Figure D-1. Wireframe views of the modeled 3D geometry for a manhole approach. Geometry shown is based on as-built specifications for the Canal Street side of Manhole 1.

Model Results

For comparison to available measurements, magnetic-field levels were calculated for the western (Canal Street) side of Manhole 1 (Location 1a) and the eastern (Salem Harbor) side of Manhole 6 (Location 6b). The calculated and measured resultants of the magnetic field were presented above in Figure 2 of the main report. The resultant of the magnetic field, however, is only a portion of the information it provides. The magnetic field is a vector quantity, possessing both a magnitude and a direction in three-dimensional space. This vector quantity can be represented by the magnitude of its three orthogonal components in the transverse (across-path), vertical, and longitudinal (along-path) directions. Comparisons of calculated and measured magnetic-field levels for as-built conditions, including plots of each vector component in addition to the resultant, are shown in Figure D-2 for the analyzed approaches to Manhole 1 and Manhole 6. The vector component profiles of the modeled magnetic field and measurements match well and this match is a sensitive indicator of congruence that demonstrates that the computational model is effectively capturing the pertinent physics and is accurately analyzing the behavior of the passive loops when accounting for all as-built specifications and line loadings.

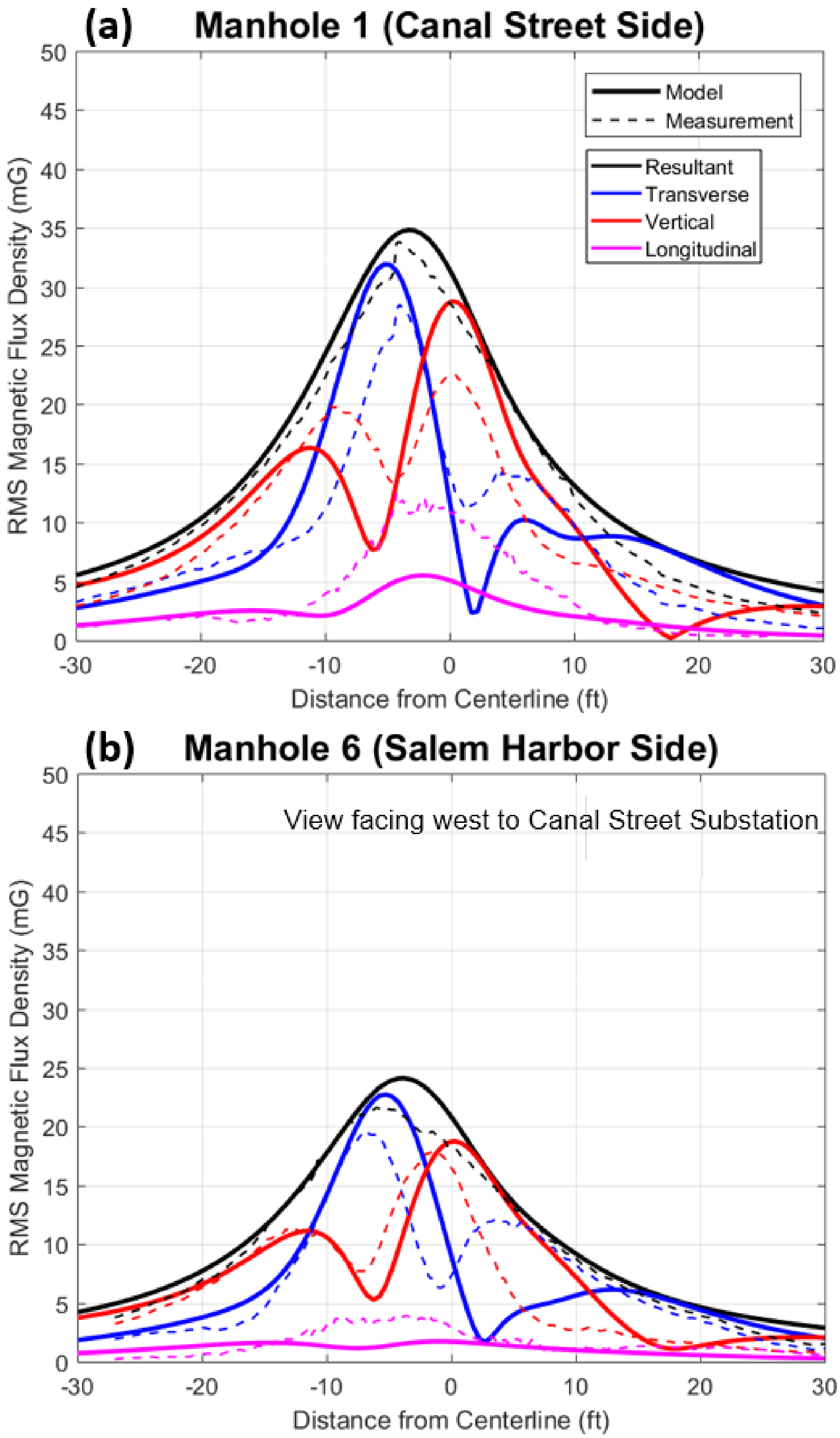


Figure D-2. Comparison of as-built calculated magnetic fields to measured magnetic fields, including vector components, for (a) the Canal Street side of Manhole 1 and (b) the Salem Harbor side of Manhole 6

As discussed in Appendix B, there were several differences between the as-built passive loop configurations and line loadings and the values applied in pre-construction analyses. Exponent investigated these differences in computational modeling and found that the imbalanced phase currents and the phase shifts measured on the GCC currents had the largest effects on the calculated magnetic-field levels for the analyzed approaches to Manholes 1 and 6.[2] Analysis of these differences is shown in Figure D-3 for Manhole 1 and Manhole 6. The orange curve in each figure assumes balanced phase currents[3] and uses an idealized 2D model to calculate induced GCC currents. When the phase currents are changed to their measured, imbalanced values, the calculated magnetic-field profile at 1 m above ground shifts horizontally by several feet and decreases slightly as shown by the green curve in each figure. When both the measured, imbalanced phase currents and the measured, phase-shifted GCC current are included in the model, the calculated magnetic-field profile is again shifted horizontally by several feet and the maximum amplitude increases by approximately 30–40%. This result, shown by the black curves in each figure, is equivalent to the model results for as-built conditions shown in Figure D-2 above. In summary, these results suggest the observed phase current imbalances shifted the magnetic-field profile horizontally by several feet, and the observed phase shift to the GCC current increased the maximum magnetic-field level by approximately 30–40% relative to a scenario with balanced phase currents.

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2 Exponent also investigated the physical differences between the as-built configurations and the pre-construction conceptual designs, such as the construction of asymmetric versus symmetric passive loops, but we found the effect of these differences to be relatively small for the analyzed configurations. For alternate configurations, such physical changes to the passive loop designs could have a larger effect.

3 Balanced phase currents used in this analysis were calculated to provide a total line loading equivalent to that measured, but with all the imbalance between phase conductors removed.

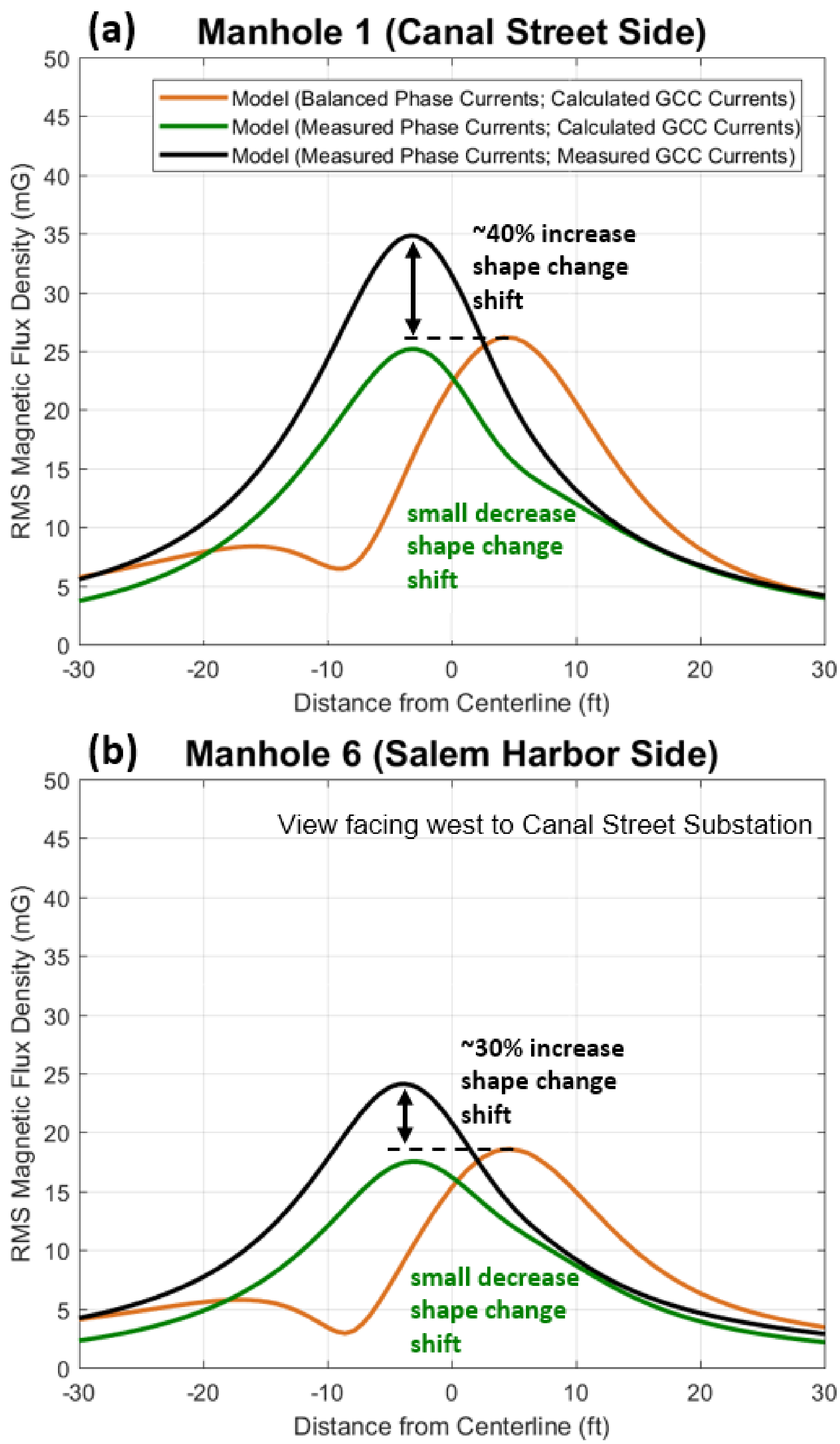

Figure D-3. Effects of phase imbalance and GCC phase angle on calculated magnetic-field levels for (a) the Canal Street side of Manhole 1 and (b) the Salem Harbor side of Manhole 6.

Appendix E

Comparison to Application Values

As discussed in Appendix C, direct comparisons of measurements to calculated values of the magnetic field for as-built conditions were not possible at measurement locations 1a through 6b because there was no safe way to access the manholes to measure GCC currents without multiple outages of the transmission lines. Measurements can, however, be compared to those values presented in the Petition, but the comparison is valid only when loading levels are consistent for measurements and modeling. The loading of the transmission lines cannot be controlled and so the best option is to use the loading levels recorded by National Grid at the time of magnetic-field measurements to scale the values from the Petition to the same loading as was recorded at the time of measurements.[1] Therefore, the ratios of the recorded line loadings at the time of measurements to full load of 250 mega-volt-amperes (MVA) at which magnetic fields were calculated in the Petition were used to scale the modeled magnetic field to that expected at the time of the measurements.

The loading at the time of these measurements varied between approximately 20 to 50 MVA. These loads are far lower than the 250 MVA loadings assumed for each line for calculation of magnetic fields in the Petition. The method just described and conceptualized in Figure E-1 was then applied to compare both the maximum calculated magnetic field above the cables in the street and the field level at a distance of 25 feet from the centerline (the approximate minimum distance from the duct bank centerline to the structure closest to any of the six manholes along the line) to measured magnetic-field levels at the same loadings.

Figure E-1 shows this scaling process for the measurement at Location 2b. At the time of these measurements, the loading on the S and T Cables was approximately 39 MVA. The magnetic-field levels calculated in Appendix 5-2 to the Petition at 250 MVA are then scaled down to a loading of 39 MVA using the ratio of their loadings: 250/39 = 6.4. In this comparison, the maximum modeled value of 71 milligauss (mG) (calculated at a load of 250 MVA) in Appendix 5-2 to the Petition would be 6.4 times lower (11 mG) to compare to the measurements at

[1] Note that in addition to the high spatial resolution measurements performed at the manhole approach (midway along the passive loops) at Location 1a and Location 6b measurements were also made at the manhole entrance with a survey wheel and methodology identical to those made at the Locations 1b through 6a discussed above.

Location 2b when the lines were operating at 39 MVA. Likewise, at a distance of ±25 feet from the centerline the magnetic-field levels of 24 mG and 26 mG modeled in Appendix 5-2 to the Petition would scale down to 3.8 mG or 4.1 mG, respectively.

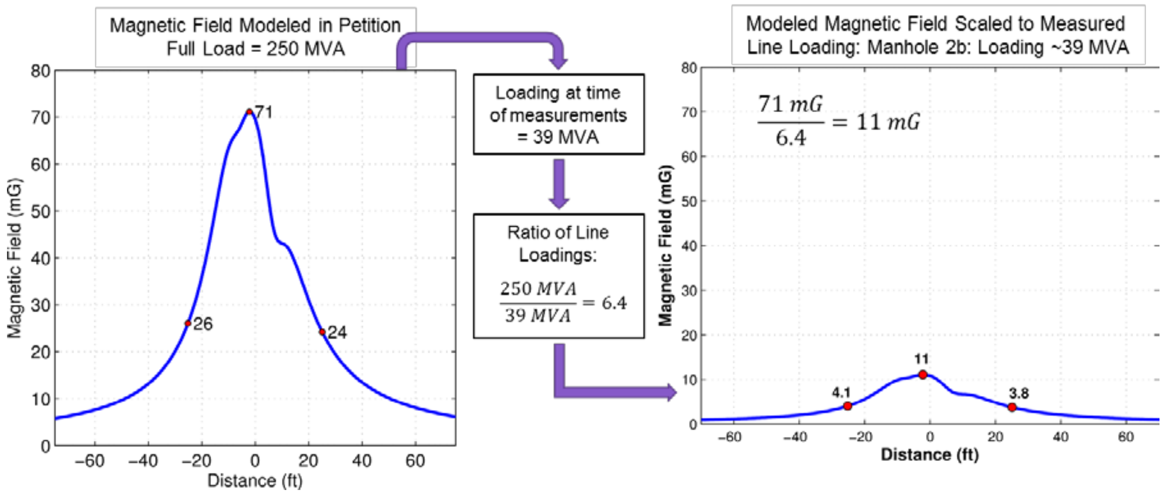

Figure E-1. Example scaling of values in Appendix 5-2 to the Petition to a lower loading for comparison with measurements

Because there are differences in the physical configuration of every manhole approach (e.g., different lengths and different separation distances) the magnetic-field levels measured at the 12 duct banks were compared to scaled-down modeled values over the cables and at ±25 feet from the centerline. For reference the maximum, minimum, and median measured and scaled model values are summarized in Table E-1. Figure 5 in the body of the report is a graphical representation of these results. A similar analysis was performed for the measurements over the horizontal configurations.[2]

2 Note the values of 4.1 and 3.8 at ±25 feet from the centerline and a maximum of 11 from the Manhole 2b shown in Table E-1 are shown in bold for reference.

Table E-1. Measured magnetic-field levels at each Manhole Entrance compared to modeled magnetic-field levels scaled by the ratio of the loading from Appendix 5-2 of the Petition.

		Measured Magnetic-Field Levels (mG)			Modeled Magnetic-Field Levels (Scaled from Petition, mG)		
		Distance from Centerline			Distance from Centerline		
Manhole Location	Load (MVA)	-25 ft	+25 ft	Max	-25 ft	+25 ft	Max
1a	41	6.3	3.2	27	4.3	3.9	12
1b	41	5.2	2.6	33	4.2	3.9	12
2a	43	3.5	2.2	29	4.5	4.1	12
2b	39	3.6	2.6	21	**4.1**	**3.8**	**11**
3a	22	2.0	3.0	21	2.2	2.1	6.1
3b	21	2.6	4.1	10	2.2	2.0	6.0
4a	36	2.6	3.0	40	3.7	3.4	10
4b	29	3.9	1.3	23	3.0	2.7	8.1
5a	46	4.4	3.2	36	4.8	4.5	13
5b	46	5.9	4.6	37	4.8	4.5	13
6a	33	3.8	3.4	26	3.4	3.1	9.3
6b	32	N/A*	4.6	34	3.3	3.1	9.1

* At this measurement location, a fence prevented measurements beyond -13 feet from the duct bank centerline.

A summary of the maximum, minimum, and median values for the measurements and modeling of the Manhole Entrance is shown in Table E-2, and a similar comparison for the Horizontal configuration is shown in Table E-3

Table E-2. Summary of maximum, minimum and median magnetic-field values measured and modeled at manhole entrances

	Measured Magnetic-Field Levels (mG)		Petition Values (mG) (Scaled Down)	
Location	Range (Min – Max)	Median	Range (Min – Max)	Median
Manhole Entrance (Max)	10–40	28	6.0–13	11
Manhole Entrance (±25 feet)	1.3–6.3*	3.4*	2.1–4.8	3.7

Table E-3. Summary of maximum, minimum and median magnetic-field values measured and modeled over the horizontal duct bank configuration

Location	Measured Magnetic-Field Levels (mG)		Petition Values (mG) (Scaled Down)	
	Range (Min–Max)	Median	Range (Min – Max)	Median
Horizontal Configuration (Max)	8.0–16	28	7.7–14	11
Horizontal Configuration (±25 feet)	1.2–3.3*	2.0*	0.5–1.1	0.8

Appendix F

Mitigation Options

Additional details regarding the theoretical functioning of the mitigation options described in the body of the report and the logistical considerations for each one are discussed in greater detail here.

Capacitive Compensation for Passive Loops

Capacitance can decrease the overall impedance of the loop, thus increasing the flow of current in the loop to enhance the cancellation of magnetic fields generated by the transmission lines. This concept is illustrated in the circuit diagram shown in Figure F-1 where the inductive impedance of the loop ($j\omega L$) can be balanced by the capacitive impedance ($-j/\omega C$). By 'tuning' the capacitance, the impedance of the loop can be altered to minimize magnetic fields ($Z_{Loop} = R + j\omega L - j/\omega C$).[1]

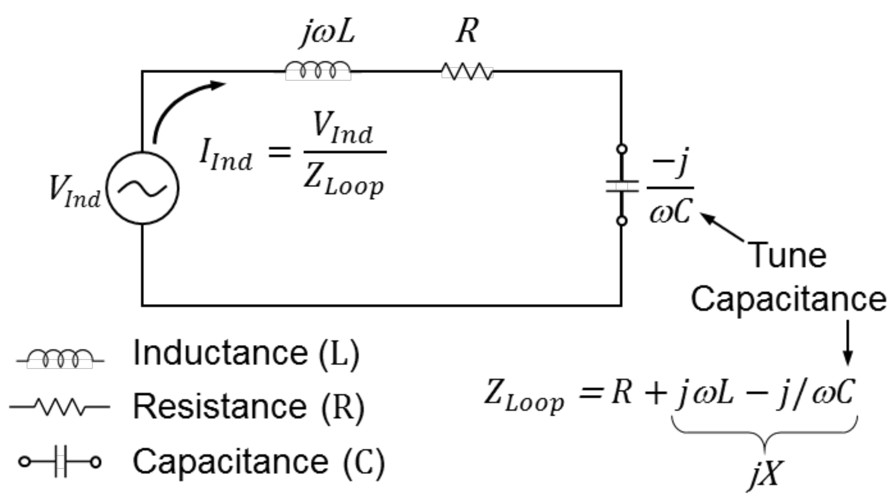

Figure F-1. Circuit diagram illustrating the theoretical functioning of a passive loop and capacitive compensation

Capacitive compensation also was considered in Appendix 5-2 to the Petition for the conceptual design evaluated (p. 2). In Appendix 5-2 to the Petition calculations, a series capacitance of 0.2

[1] Note the resistance (R) of the loop is determined by the material properties, length, and diameter of the conductor and is unaffected by the capacitive compensation.

Farads (F) was used to reduce the reactance of the loop.[2] The original application did not, however, consider the feasibility of installing this level of capacitance in the manholes. Additional analysis performed by Burns & McDonnell indicated that the large amount of capacitance required for passive loop compensation (on the order of 0.2 F) would require a bank of electrolytic capacitors that would exceed the size of the manholes themselves. In addition, the electrolytic capacitors would require ventilation as well as periodic maintenance and line outages. Finally, even if the necessary number of capacitors could fit in the manholes, installing and "tuning" them would require multiple and lengthy outages at each manhole. Capacitive compensation is therefore not considered a viable option for further reducing magnetic-field levels at the manholes.

Active Loops

An additional option for reducing magnetic-field levels is to inject current on the passive loops to increase the degree of cancellation of the magnetic field from the phase conductors. A conceptual illustration of how the active loops would work is shown in Figure F-2. For the manholes under consideration here, four separate active loops (color-coded purple and blue for one side of the manhole and orange and green for the other side) are described.

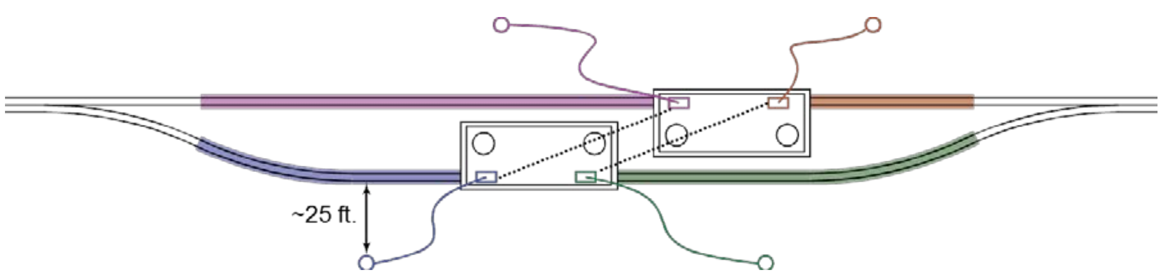

Figure F-2. Conceptual illustration of requirements for active loops

Active loops require a small sensing antenna at the location of desired magnetic-field reduction (in this case likely somewhere approximately 25 feet from the duct bank as shown by the small colored circles in Figure F-2). The measurements from these small antennas would need to be

[2] The 0.2 F capacitor for compensation was determined using a parametric sweep of values within the COMSOL model.

brought back into the manholes (thin colored lines from the small circles back to duct banks). Within the manholes themselves, a low-voltage alternating current source would be needed to inject a current onto each of the passive loops, making them active loops. A microcontroller or other logic device would then need to be developed along with an optimization feedback algorithm to adjust the amount of current being driven on each individual passive loop so as to minimize the measured magnetic field. Optimal reduction would require communication between each pair of loops/algorithms as shown by the dashed black lines in Figure F-2. The operational flow diagram describing the continuous process which would need to occur for the active loops is shown below in Figure F-3. The feedback mechanism by which active loops operate would reduce magnetic-field levels at the locations of the small sensing antennas, but by generating additional currents it is possible that magnetic-field levels at other locations could actually increase (e.g., over the duct bank).

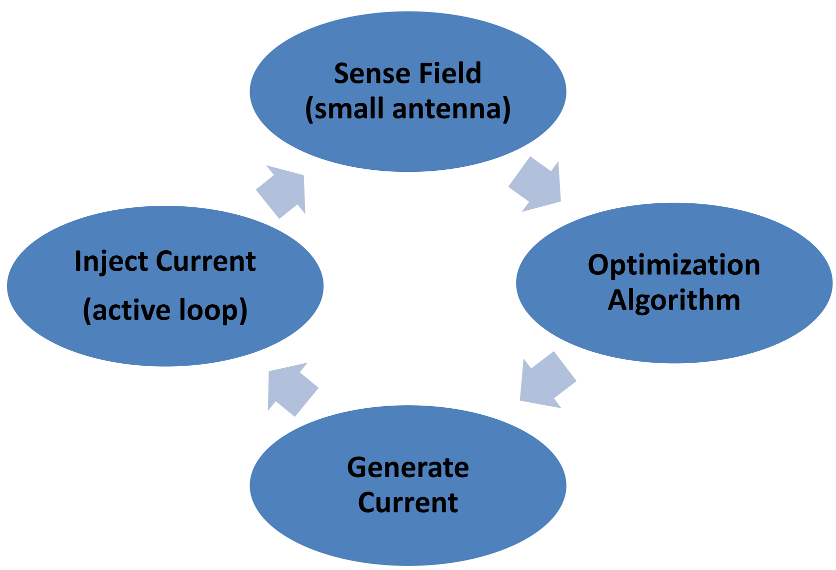

Figure F-3. Operational flow diagram describing the functioning of active loops for magnetic-field reduction

While the theoretical functioning of active loops has been demonstrated mathematically, Exponent is unaware of any functioning active loops installed by any utility in North America, and this would therefore be a theoretical solution with no certainty of effectiveness. In addition, active loops would require the excavation of the street to place the four sensing antennas, a low-voltage alternating current power source to drive the active loops, a low-voltage direct current power source to power any microprocessor or digital logic array, and development of an optimal feedback algorithm and optimization for each passive loop pair. Active loops are therefore not considered a viable option for further reducing magnetic-field levels at the manholes.

Shielding

Another option for reducing magnetic fields is shielding the magnetic fields with metal plates. Two forms of shielding are described in the literature. One form is ferromagnetic shielding, in which the electron orientation inside the ferromagnetic material redirects the magnetic field (illustrative example shown in Figure F-4). Another form involves layers of high-conductivity materials such as copper or aluminum in which eddy currents flow, inducing a canceling magnetic field (not shown). In general, shielding could be placed either around each cable phase or by installing shielding plates over the transmission lines at the manhole approaches.

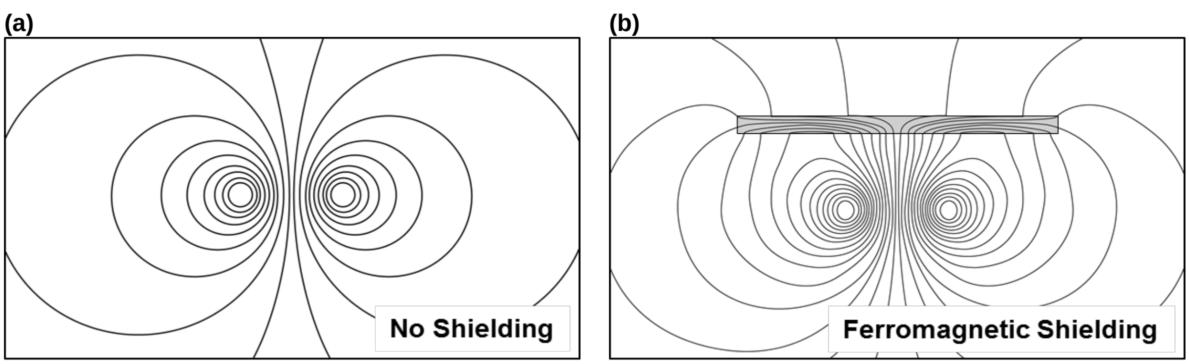

Figure F-4. Illustration of magnetic-field reduction via ferromagnetic shielding

The installation of shielding around the individual cables could potentially be done during installation, but installing this option post-construction is completely impractical. Although shielding with metallic plates over the transmission line duct banks would be relatively easier to install[3] and could reduce magnetic-field levels directly above the duct bank, it is likely that such an installation would increase magnetic-field levels away from the duct bank (e.g., at structures ±25 feet away). In addition, the close proximity of the conducting or ferromagnetic plates

[3] Additional in-street construction would be required at each manhole to install the plates.

would also cause heating of the transmission line cables, which would reduce the cable ampacity and potentially decrease the lifetime of the cables. A qualitative illustration of the effect that conductive plates can have on the temperature of transmission line cables is shown in Figure F-5.

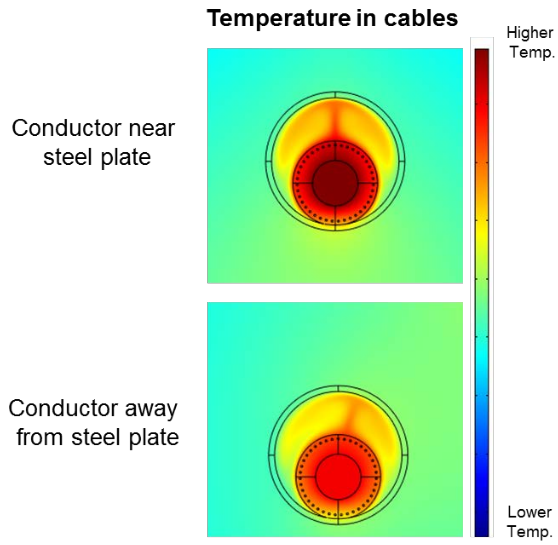

Figure F-5. Example calculation of the increased operating temperature of an underground transmission line cable near a steel plate (top) and away from a steel plate (bottom).

Therefore, installing shielding over the duct banks is not considered a viable option for reducing magnetic-field levels at manholes.

Appendix G

Calibration Certificates

Certificate of Calibration

The calibration of this instrument was controlled by documented procedures as outlined on the attached Certificate of Testing Operations and Accuracy Report using equipment traceable to N.I.S.T., ISO 17025, and ANIZ540-1 COMPLIANT.

Instrument Model: EMDEX II

Frequency: 60 Hertz

Serial Number: 3363

Date of Calibration: 6/27/2016

Re-Calibration suggested at one year from above date.

EMDEX LLC
EMDEX-LLC
1356 Beaver Creek Drive
Patterson, California 95363
(408) 866-7266

H. Christopher Hooper
Calibration Inspector

Certificate of Calibration

The calibration of this instrument was controlled by documented procedures as outlined on the attached Certificate of Testing Operations and Accuracy Report using equipment traceable to N.I.S.T., ISO 17025, and ANIZ540-1 COMPLIANT.

Instrument Model: EMDEX II

Frequency: 60 Hertz

Serial Number: 3074

Date of Calibration: 6/27/2016

Re-Calibration suggested at one year from above date.

EMDEX LLC
EMDEX-LLC
1356 Beaver Creek Drive
Patterson, California 95363
(408) 866-7266

H. Christopher Hooper
Calibration Inspector

Kestrel®
Weather & Environmental Meters
by NK

Certificate of Conformity

This instrument was produced under rigorous factory production control and documented standard procedures. It was individually visually inspected, leak tested and function tested for display, backlight, button and software performance. The accuracy of each of its primary measurements was individually calibrated and/or tested against standards traceable to the National Institute of Standards and Technology ("NIST") or calibrated intermediary standards. This instrument is certified to have performed at the time of manufacture in compliance with the following specifications as they apply to this meter's specific model, measurements and features.

Methods Used in Calibration and Testing

Wind Speed:

The Kestrel Weather & Environmental Meter impeller installed in this unit was individually tested in a subsonic wind tunnel operating at approximately 300 fpm (1.5 m/s) and 1200 fpm (6.1 m/s) monitored by a Gill Instruments Model 1350 ultrasonic time-of-flight anemometer. The Standard's maximum combined uncertainty is +/–1.04% within the airspeed range 706.6 to 3923.9 fpm (3.59 to 19.93 m/s), and +/–1.66% within the airspeed range 166.6 to 706.6 fpm (0.85 to 3.59 m/s).

Temperature:

Temperature response is verified in comparison with a Eutechnics 4600 Precision Thermometer or a standard Kestrel 4000 Weather & Environmental Meter calibrated weekly against the Eutechnics 4600. The Eutechnics 4600 is calibrated annually and is traceable to NIST with a system accuracy of +/– 0.05 °C.

Direction / Heading

The sensitivity of the magnetic directional sensor is verified at the component level by applying a magnetic field to the sensor and measuring the signal output at 4 points, as well as after assembly by orienting the unit to the cardinal directions and measuring the magnetic field output. In both cases, the compass output must be accurate to within +/– 5 degrees.

Relative Humidity:

Relative humidity receives a two-point calibration in humidity and temperature controlled chambers at 75.3% RH and 32.8% RH at 25° C. The calibration tanks are monitored with an Edgetech Model 2002 DewPrime II Standard Chilled Mirror Hygrometer. Following calibration, performance is further verified at an RH of approximately 43.2% against the Edgetech Hygrometer. The Edgetech Hygrometer is calibrated annually and is traceable to NIST with a maximum relative expanded uncertainty of +/– 0.2% RH.

Barometric Pressure:

Pressure response is verified against a Vaisala PTB210A Digital Barometer or a standard Kestrel 4000 Weather & Environmental Meter calibrated weekly against the Vaisala Barometer. The Vaisala Barometer is calibrated annually and is traceable to NIST with an accuracy of +/-0.15 hPa at +20°C defined as the root sum of the squares (RSS) of end point non-linearity, hysteresis error, repeatability error and calibration uncertainty at room temperature.

Approved By:

Michael Naughton, Engineering Manager

The enclosed Kestrel Weather & Environmental Meter was manufactured by Nielsen-Kellerman Co. at its facilities located at 21 Creek Circle, Boothwyn, PA 19061 USA.