Electric and Magnetic Field (EMF) Analysis for the Mystic-to-Woburn 211-514x and 211-514y, 115-kV Transmission Lines

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March 6, 2015

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1 Introduction and Summary

NSTAR Electric Company *d/b/a* Eversource Energy ("Eversource"), has proposed to supplement an existing HPFF 115-kV line (211-514x) by installing a new HPFF 115-kV line (211-514y) parallel to this line along the existing line route from Mystic Substation in Everett, MA to Woburn Substation in Woburn, MA. Both the existing and proposed lines are underground.

Eversource requested that Gradient perform an independent assessment of the electric and magnetic field (EMF) impacts associated with the planned project. We conservatively modeled EMF using peak 2018 projected line loadings provided by Eversource for two scenarios: one with the proposed line included, and one with the existing line only (Velez, 2015).

As described in this report, we found that magnetic field levels calculated to exist above the underground cables are well below the International Commission on Non-Ionizing Radiation Protection (ICNIRP) health-based guidelines for public exposure to EMF (2,000 mG). In addition, all field values are below the Massachusetts ROW-edge magnetic field guideline value of 85 mG (MAEFSB, 2010). Since underground lines produce no aboveground electric fields and all proposed lines associated with the substation are underground, there will be no aboveground post-project electric fields.

We found that the maximum magnetic field value generated by the combined effects of the two lines at peak operation load is 3.61 mG. It is located above the centerline of the proposed 115-kV line. In all models, field values decrease rapidly with lateral distance from the lines. The maximum magnetic field value generated at peak operation load in the scenario where no new line is installed is 4.10 mG.

In this report, Section 2 describes the nature of EMF and provides values for EMF levels both from common sources and from available EMF exposure guidelines. Section 3 outlines the EMF modeling procedures for calculating magnetic field strengths as a function of lateral distance from an electric transmission or distribution line, as well as providing graphical and tabular results. Section 4 summarizes the conclusions, and Section 5 lists the bibliographic references.

2 Nature of Electric and Magnetic Fields

All matter contains electrically charged particles. Most objects are electrically neutral because positive and negative charges are present in equal numbers. When the balance of electric charges is altered, we experience electrical effects, such as the static electricity attraction between a comb and our hair, or drawing sparks after walking on a synthetic rug in the wintertime. Electrical effects occur both in nature and through our society's use of electric power (generation, transmission, consumption).

2.1 Units for EMF Are Kilovolts per Meter (kV/m) and Milligauss (mG)

The electrical tension on utility power lines is expressed in volts or kilovolts (kV; 1 kV = 1,000 V). Voltage is the "pressure" of the electricity, and can be envisioned as analogous to the pressure of water in a plumbing system. The existence of a voltage difference between power lines and ground results in an "electric field," usually expressed in units of kilovolts per meter (kV/m). The size of the electric field depends on the voltage, the separation between lines and ground, and other factors.

Power lines also carry an electric current that creates a "magnetic field." The units for electric current are amperes (A) and are a measure of the "flow" of electricity. Electric current can be envisioned as analogous to the flow of water in a plumbing system. The magnetic field produced by an electric current is usually expressed in units of gauss (G) or milligauss (mG), where 1 G = 1,000 mG. Another unit for magnetic field levels is the microtesla (μT), where 1 μT = 10 mG. The size of the magnetic field depends on the electric current, the distance to the current-carrying conductor, and other factors.

2.2 There Are Many Natural and Man-made Sources of EMF

Everyone experiences a variety of natural and man-made electric and magnetic fields. Electric and magnetic field levels can be slowly varying or steady (often called "DC fields"), or can vary in time (often called "AC fields"). When the time variation of interest corresponds to that of power line currents, *i.e.*, 60 cycles per second, the fields are called "60-Hz" EMF. Man-made magnetic fields are common in everyday life. For example, many childhood toys contain magnets. Such permanent magnets generate strong, steady magnetic fields. Typical toy magnets (*e.g.*, "refrigerator door" magnets) have fields of 100,000 to 500,000 mG. On a larger scale, the earth's core creates a steady magnetic field that can be easily demonstrated with a compass needle. The size of the earth's magnetic field in the northern US is about 550 mG (over a hundred times smaller than fields generated by "refrigerator door" magnets). Knowing the strength of the earth's magnetic field provides a perspective on the size of power line magnetic fields. The earth's steady field does not have the 60-Hz time variation characteristic of power line EMF, but is experienced as a changing magnetic field as one moves around in it. Alternatively, moving magnets generate time-varying magnetic fields. For example, a magnet spinning at 60 times a second will produce a 60-Hz magnetic field indistinguishable from that found near electric power lines carrying the appropriate level of electric current. Even the rotating steel-belted radial tires on a car produce time-varying magnetic fields. And although magnetic resonance imaging (MRI) is a diagnostic procedure that puts humans in much larger, but steady, magnetic fields (*e.g.*, 20,000,000 mG), it is preferred over taking an X-ray picture. Contrary to X-rays, MRIs have no known health risks (other than the large forces exerted on nearby steel objects).

2.3 Power-frequency EMF Are Found Near Electric Lines and Appliances

Electric power transmission lines, distribution lines, and electric wiring in buildings carry AC currents and voltages that change size and direction at a frequency of 60 Hz. These 60-Hz currents and voltages create 60-Hz EMF nearby. The size of the magnetic field is proportional to the line current, and the size of the electric field is proportional to the line voltage. The EMF associated with electrical wires and electrical equipment decrease rapidly with increasing distance away from the electrical wires.

When EMF derives from different sources (*e.g.*, adjacent wires), the size of the net EMF produced will be somewhere in the range between the sum of EMF from the individual sources and the difference of the EMF from the individual sources. Thus, EMF may partially add, or partially cancel, but generally, because adjacent wires are often carrying current in opposite directions, the EMF produced tends to be cancelled. Inside residences, typical baseline 60-Hz magnetic fields (far away from appliances) range from 0.5 to 5.0 mG. EMF in the home arise from electric appliances, indoor wiring, grounding currents on pipes and ground wires, and outdoor distribution or transmission circuits. All these separate power-line magnetic fields add or subtract from the steady field of the earth (570 mG), so that the sum total magnetic field in the home has both a steady part and a time-varying part.

Higher 60-Hz magnetic field levels are found near operating appliances. For example, can openers, mixers, blenders, refrigerators, fluorescent lamps, electric ranges, clothes washers, toasters, portable heaters, vacuum cleaners, electric tools, and many other appliances generate magnetic fields of size 40 to 300 mG at distances of 1 foot (NIEHS, 2002). Magnetic fields from personal care appliances held within ½ foot (*e.g.*, shavers, hair dryers, massagers) can produce 600 to 700 mG. At school and in the workplace, lights, motors, copy machines, vending machines, video-display terminals, pencil sharpeners, electric tools, and electric heaters are all sources of 60-Hz magnetic fields.

2.4 State, National, and International Guidelines for EMF Are Available

The US has no federal standards limiting occupational or residential exposure to 60-Hz EMF. Table 2.1 shows guidelines suggested by national and world health organizations. The levels shown on Table 2.1 are designed to be protective against any adverse health effects. The limit values should not be viewed as demarcation lines between safe and dangerous levels of EMF, but rather, levels that assure safety with an adequate margin of safety to allow for uncertainties in the science. Table 2.2 lists guidelines that have been adopted by various states in the US. State guidelines are not health-effect based, and have been typically adopted to maintain the *status quo* for EMF on and near transmission line ROWs.

Table 2.1 60-Hz EMF Guidelines Established by Health and Safety Organizations

Organization	Magnetic Field	Electric Field
American Conference of Governmental and Industrial Hygienists (ACGIH) (occupational)	10,000 mG[a] 1,000 mG[b]	25 kV/m[a] 1 kV/m[b]
International Commission on Non-Ionizing Radiation Protection (ICNIRP) (general public, continuous exposure)	**2,000 mG**	**4.2 kV/m**
Non-Ionizing Radiation (NIR) Committee of the American Industrial Hygiene Assoc. (AIHA) endorsed (in 2003) ICNIRP's occupational EMF levels for workers	4,170 mG	8.3 kV/m
Institute of Electrical and Electronics Engineers (IEEE) Standard C95.6 (general public, continuous exposure)	9,040 mG	5.0 kV/m
UK, National Radiological Protection Board (NRPB) [now Health Protection Agency (HPA)]	2,000 mG	4.2 kV/m
Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), Draft Standard, Dec. 2006[c]	3,000 mG	4.2 kV/m
*Comparison to **steady** [see text] (DC) EMF, encountered as EMF outside the 60-Hz frequency range:*		
Earth's magnetic field and atmospheric electric fields, steady levels, typical of environmental exposure[d]	550 mG	0.2 kV/m up to > 12 kV/m
Magnetic Resonance Imaging Scan, static magnetic field intensity[d]	20,000,000 mG	–

Notes:
(a) The ACGIH (2010a) guidelines for the general worker (ACGIH, 2010b, p124-127).
(b) The ACGIH (2010a) guideline for workers with cardiac pacemakers (ACGIH, 2010b, p124-127).
(c) ARPANSA (2006, 2008).
(d) These EMF are steady fields, and do not vary in time at the characteristic 60 cycles-per-second that power-line fields do. However, if a person moves in the presence of these fields, the body experiences a time-varying field.

Table 2.2 State EMF Standards and Guidelines for Transmission Lines

State	Line Voltage (kV)	Electric Field (kV/m)		Magnetic Field (mG)	
		On ROW	Edge ROW	On ROW	Edge ROW
Florida[a]	69 – 230	8.0	2.0[b]		150
	500	10.0			200, 250[c]
Massachusetts			**1.8**		**85**
Minnesota		8.0			
Montana		7.0[d]	1.0[e]		
New Jersey			3.0		
New York[c]		11.8 11.0[f] 7.0[d]	1.6		200
Oregon		9.0			

Notes:
ROW = right of way; mG = milligauss; kV/m = kilovolts per meter.
(a) Magnetic fields for winter-normal, *i.e.*, at maximum current-carrying capability of the conductors.
(b) Includes the property boundary of a substation.
(c) 500 kV double-circuit lines built on existing ROWs.
(d) Maximum for highway crossings.
(e) May be waived by the landowner.
(f) Maximum for private road crossings.
Sources: NIEHS (2002); FLDEP (2008).

3 Modeled Magnetic Fields

3.1 Software Programs Used for Modeling EMF

We used the FIELDS computer program, designed by Southern California Edison, to calculate magnetic field strengths from the proposed lines at cross-sections perpendicular to the lines as a function of voltage, current, and distance. This program operates using Maxwell's equations, which accurately describe the laws of physics as they apply to electricity and magnetism. Modeled fields using this program are both precise and accurate for the input data utilized. Results of the models have been checked extensively against each other and against other software (*e.g.*, "CORONA" from the Bonneville Power Administration, US Dept. of Energy) to ensure that the implementation of the laws of physics are consistent. In these validation tests, program results for EMF were found to be in very good agreement with each other.

3.2 Power-Line Flows

Magnetic fields produced by the proposed lines were modeled using line loadings communicated by Eversource. The current per phase satisfies the relationship:

(Eq. 3.1) $$S = \sqrt{3} \times V \times I_{phase}$$

where:

S	=	the power in kilovolt-amps (kVA)
V	=	the line voltage in kilovolts (kV)
I_{phase}	=	the current per phase in amps (A).

Thus, the current per phase conductor is:

(Eq. 3.2) $$I_{phase} = \frac{S}{\sqrt{3} \times V}$$

Real power is given in megawatts (MW) [***P***], and apparent power in megavolt-amps (MVA) [***S***].[1] To convert between power quoted in megawatts to megavolt-amps, one must divide by the power factor.

Electric current values provided by Eversource are summarized in Table 3.1 (Velez, 2015). Eversource determined these currents by power-flow modeling for the future year 2018 assuming that all of the other Greater Boston solution projects were complete, that all lines are in service, and using the peak-load

[1] MVA is apparent power and is the vector sum of real (active) and imaginary (reactive) power. MW and MVA are not the same unless power factor = 1.0, which in a practical AC circuit is generally not the case.

generation dispatch from the Greater Boston needs assessment studies that would produce the highest current flow on the existing Line 211-514.

Table 3.1 Electric Currents for Proposed Project

Existing Line Only, 2018 Projected Load			
Transmission Line	**Projected (2018) Future Average Load Current (Amps)**	**Projected (2018) Future Peak Load Current (Amps)**	**Direction of Current**
Existing 211-514x (115-kV line)	155	840	Woburn to Mystic
Existing Line and New Line, 2018 Projected Load			
Transmission Line	**Projected (2018) Future Average Load Current (Amps)**	**Projected (2018) Future Peak Load Current (Amps)**	**Direction of Current**
Existing 211-514x (115-kV line)	124	497	Woburn to Mystic
Proposed 211-514y (115-kV line)	162	704	Woburn to Mystic

3.3 EMF Model for the Proposed Transmission and Distribution Lines

EMF modeling of the proposed underground lines included calculation of magnetic fields levels expected to exist 3 feet above the ground surface for the peak 2018 loading on the lines in both scenarios described above (with and without the new 115-kV line). We modeled a cross-sectional view of magnetic field strength as a function of distance perpendicular to the direction of current along a segment of the route where power lines are parallel and straight. Since aboveground electric fields from underground circuits are zero due to the shielding effects of the metal pipe and the earth, no electric field modeling was needed.

Eversource provided Gradient with proposed configuration schematics as well as circuit specifications. (Eversource, 2015; select drawings are provided as Appendix A).

The model loadings on the two lines are shown in Table 3.1 and discussed in Section 3.2. The existing 115-kV line consists of three 115-kV 1250-kcmil HPFF cables arranged in a triangular configuration within a 6-5/8" steel pipe. The proposed 115-kV line consists of three 115-kV 2500-kcmil HPFF pipe type cables arranged in a triangular configuration within a 8-5/8" steel pipe. In the scenario containing both existing and proposed pipes, the center-to-center distance between the two pipe ducts is 12.083 feet (Velez, 2015). All circuits are at an approximate depth of 4.5 feet (Velez, 2015). Figure 3.1, provided by Eversource, shows a cross-section of the typical offset between the existing and proposed lines (Eversource, 2015).

The ferromagnetic steel pipes enclosing each set of transmission line phase conductors considerably attenuate the magnetic field that would be produced by the phase conductors alone, in the absence of the steel pipe. Estimates of shielding efficiency by ferromagnetic materials suggest that for bundled 3-phase cables, surrounding ferromagnetic material reduces the magnetic fields by 25- to 30-fold below what is calculated for the unshielded cables, although shielding factors of about 100 have been achieved in some cases. Anticipated field values are therefore at least ten times smaller than the values calculated for the transmission lines without taking into account shielding effects (Xu and Yang, 1996; EPRI, 1993; EPRI and HVTRC, 1994). This ten-fold attenuation is therefore included in our models.

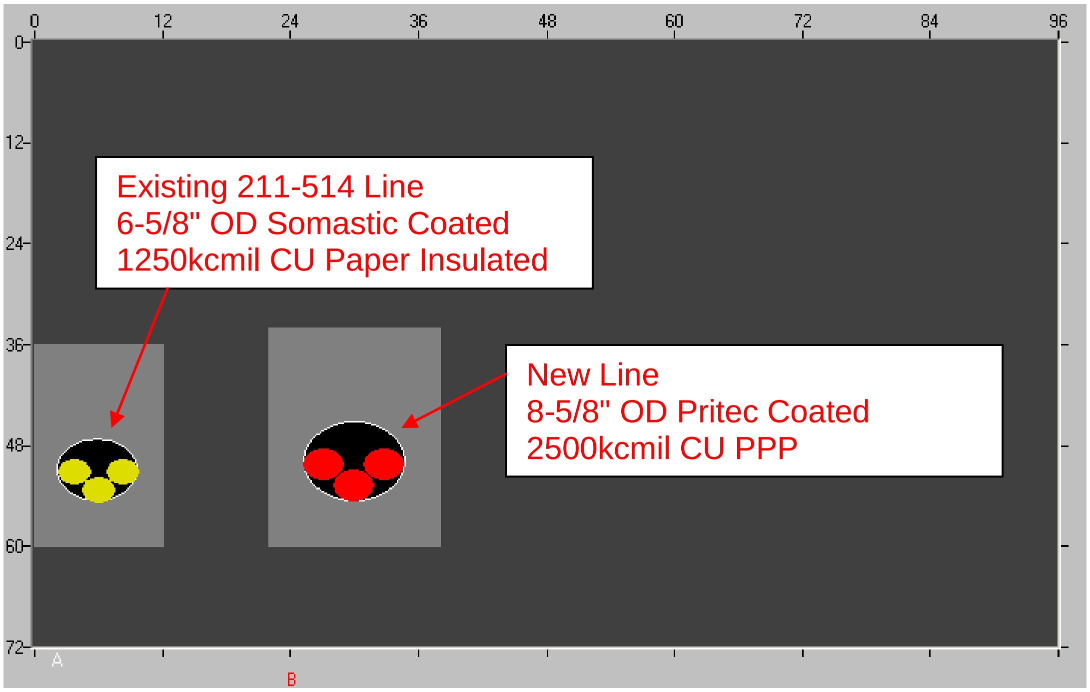

Figure 3.1 Schematic of the Configuration for the Existing and Proposed Lines. The *x-y* coordinate system origin is at the street surface in the upper left corner of the figure. The conductor locations shown are illustrative, and the figure is not to scale. Typical depth variations created during installation would have a small effect on the calculated magnetic field values.

3.4 EMF Modeling Results

Figure 3.2, below, shows the calculated magnetic field for 2018 average loading conditions at 3 feet above ground surface (including the 10-fold magnetic field attenuation by the steel pipe) for the existing line only (green) and the configuration containing the existing and proposed lines (pink). Each gray diamond represents the location of a phase conductors present in the configuration containing only the existing transmission line, and each black diamond represents the location of a phase conductor present in the configuration containing both the existing and proposed transmission lines. As shown in the figure, the modeled magnetic fields due to the existing line only reach a maximum at 0.76 mG and fall to 0.10 mG a distance of 20 feet laterally on either side of the centerline of the circuit. The modeled magnetic fields due to the existing line and proposed lines together reach a maximum at 0.83 mG and fall to 0.13 mG at x=0 and 0.17 mG at x=50.

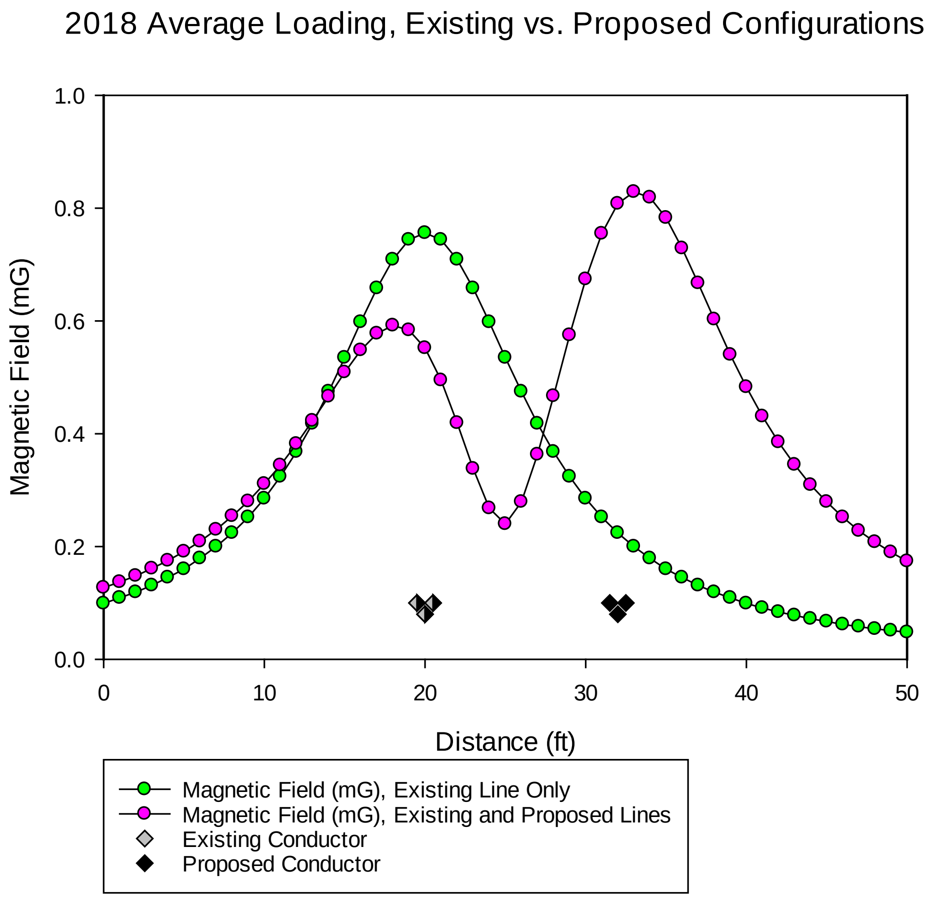

Figure 3.2 Magnetic Field Values for 2018 Average Loading Conditions, Existing vs Proposed Configurations. The maximum magnetic field value for the existing line only is 0.76 mG, located at *x*=20. The magnetic field values drop rapidly with lateral distance from the lines, falling to 0.10 mG at 20 feet to either side of the centerline of the existing conductors. The maximum magnetic field value for the configuration containing both lines is 0.83 mG, located at *x*=33. The magnetic field values drop rapidly with lateral distance from the lines, falling to 0.13 mG at x=0, and 0.17 mG at x=50.

Figure 3.3, below, shows the calculated magnetic field for 2018 peak loading conditions at 3 feet above ground surface for the existing line only (green) and the configuration containing the existing and proposed lines (pink). Each gray diamond represents the location of a phase conductors present in the configuration containing only the existing transmission line, and each black diamond represents the location of a phase conductor present in the configuration containing both the existing and proposed transmission lines. As shown in the figure, the modeled magnetic fields due to the existing line only reach a maximum at 4.10 mG and fall to 0.54 mG a distance of 20 feet laterally on either side of the centerline of the circuit. The modeled magnetic fields due to the existing line and proposed lines together reach a maximum at 3.61 mG and fall to 0.52 mG at x=0 and 0.74 mG at x=50.

The modeled magnetic field values all fall below the Massachusetts guideline for magnetic field values (85 mG, see Table 2.2).

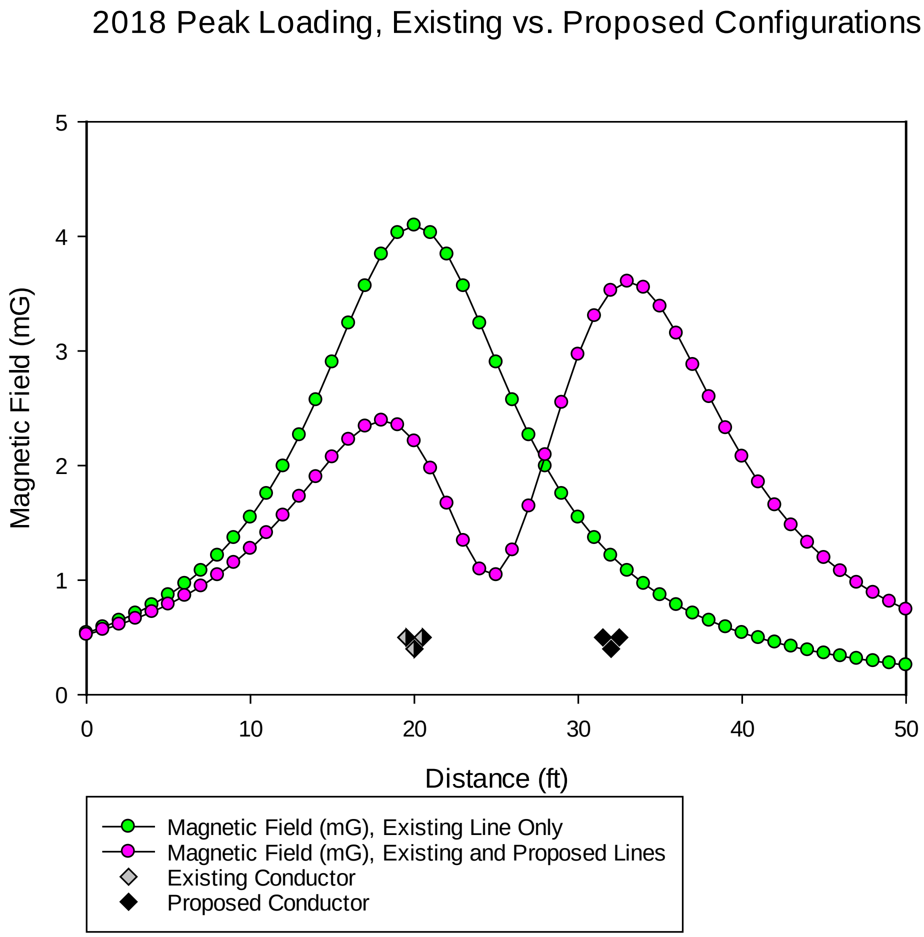

Figure 3.3 Magnetic Field Values for 2018 Peak Loading Conditions, Existing vs Proposed Configurations. The maximum magnetic field value for the existing line only is 4.10 mG located at x=20. The magnetic field values drop rapidly with lateral distance from the lines, falling to 0.54 mG at 20 feet from the centerline of the conductors. The maximum magnetic field value for the configuration containing both lines is 3.61 mG, located at *x*=33. The magnetic field values drop rapidly with lateral distance from the lines, falling to 0.52 mG at x=0, and 0.74 mG at x=50.

4 Conclusions

Gradient calculated the 3 feet above ground-surface magnetic field levels projected to exist above the existing and proposed configurations of the Mystic-to-Woburn project. Table 4.1, below, summarizes the magnetic field results for the EMF modeling. All fields represent modeled values for the projected peak and average operational line loads (2018). Because all circuits are underground, electric fields associated with all lines are zero.

Table 4.1 Modeled Magnetic Fields 3 Feet Above Ground Surface

Scenario	Maximum Magnetic Field (mG)
Existing Line Only, Peak Load	4.10
Existing Line Only, Average Load	0.76
Existing and Proposed Lines, Peak Load	3.61
Existing and Proposed Lines, Average Load	0.83

Table 4.1 demonstrates that the maximum magnetic field levels predicted along the underground routes of the existing and proposed lines fall well below accepted health-based guidelines for allowable public exposure to magnetic fields (2,000 mG) (ICNIRP, 2010). In addition, all field levels along the distribution line routes, including directly overhead, fall below the Massachusetts ROW-edge magnetic-field guideline of 85 mG (see Table 2.2). Overall, there is no expectation of adverse health effects due to the EMF impact from the proposed underground circuit project.

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