JOURNAL OF BIOELECTRICITY, 1(3), 329–338 (1982)

BIOELECTRIC CONSIDERATIONS IN THE DESIGN OF HIGH-VOLTAGE POWER LINES

Maria Reichmanis and Andrew A. Marino
Department of Orthopaedic Surgery
Louisiana State University Medical Center
Shreveport, LA 71130-3932

ABSTRACT

Public-health considerations require that all practical steps be taken to minimize the environmental electric and magnetic fields of high-voltage power lines. These fields are influenced not only by the line's operating voltage, but also by various design features including line configuration, phase-spacing, line height, and cable diameter. The largest effect is associated with line configuration. Beyond about 50 meters, the fields of a horizontal line are less than that of the equivalent vertical line; they become progressively more so with increasing distance. As a consequence, for a line having a given energy-carrying capacity, the horizontal configuration minimizes the ground-level fields at points beyond the right-of-way. None of the other design features considered had a significant effect on the fields.

INTRODUCTION

High-voltage power lines (HVPL) give rise to electric and magnetic fields that extend laterally from the lines for considerable distances (1). There has been much recent interest on the part of the industry, government and the general public in the possible environmental effects of such fields, especially the hazards they may pose for human health. In laboratory studies, low- frequency fields have been found to cause biological effects in animals (2-4) and humans (5-7); in epidemiological studies effects due to environmental fields have been reported (8-10). The fields studied ranged as low as those corresponding to several thousand feet from typical HVPL.

The mode of action by which electromagnetic fields induce biological effects is largely unexplored. There is presently no precise indication of an exposure threshold, either in duration or field strength, for the onset of effects, nor has the degree to which many of the effects constitute a human health hazard been determined. Pending further investigation of these questions, medical-ethical and public-health guidelines mandate that human exposure to power-line fields be minimized as far as practicable. It is, therefore, worthwhile to consider whether relatively simple changes in line geometry can have a significant impact on the magnitude of the resulting fields. For any given HVPL, major design considerations include the configuration (whether horizontal or vertical), phase spacing, line height, and conductor diameter. We analyzed the impact of these parameters on power-line fields. To simply the problem, the influence of second-order factors such as ground wires and bundled conductors was not considered. We used the mean height of the vertical configuration as being most comparable to the height of the horizontal line.

RESULTS

The electric field of a ground-return HVPL can be found by the method of images (1). Assuming the earth is a good conductor, the ground-level electric field of a 3-phase line having angular frequency ω is

$$E(x) = A\cos\omega t + B\sin\omega t,$$

where A and B are constants, which depend on the line configuration, operating voltage, and the distance from the center-line. The maximum ground-level field is therefore

$$E_{max} = A\cos\varphi + B\sin\varphi,\ \varphi = \tan^{-1}(B/A),$$

which can be reduced to

$$E_{max} = (A^2 + B^2)^{1/2}.$$

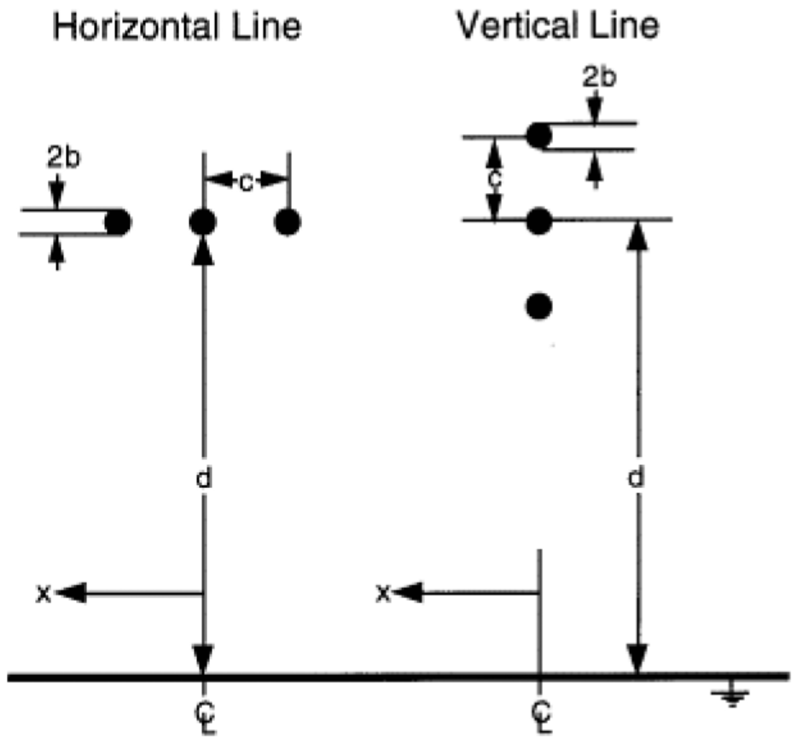

FIGURE 1. Vertical and horizontal 3-phase ground-return transmission lines. Cable radius, b; line height, d; phase-spacing, c; lateral distance from the centerline, x.

We examined the variation of E_{max}/V, the maximum ground-level electric field per unit of line voltage, for both horizontal and vertical lines (Figure 1); the exact field equations are listed in Appendix 1.

Typical values of E_{max}/V for both the horizontal and vertical configuration are shown in Figure 2. The maximum electric field of a horizontal line is displaced from the center-line, and the location and magnitudes of the maxima depend on the specific values of phase-spacing, line height, and cable diameter. The field of a horizontal line may be greater or less than that of the equivalent vertical line at nearby points (Figure 2, insert), but is less at more distant points. This difference becomes more pronounced with increasing distance; for example, E_{max}/V of the vertical line exceeds the value for a horizontal line by 20% at 50 meters, but by 600% at 1000 meters (Figure 2; see also Table 1).

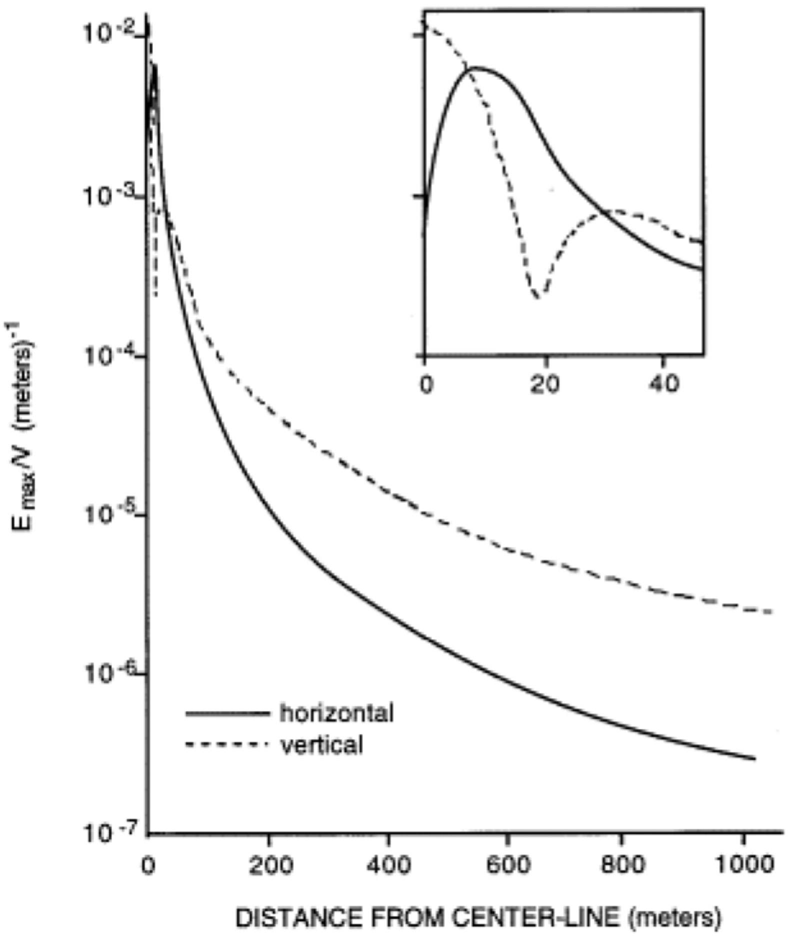

FIGURE 2. E_{max}/V vs. distance for horizontal and vertical lines (b = 0.01 m, c = 4 m, d = 15 m).

TABLE 1. Difference between the horizontal and vertical lines of Figure 2. The difference in ground-level electric field strength increases with increasing distance from the center of the right-of-way (ROW)

	DISTANCE FROM CENTER OF ROW (m)		
E_{max}/V (m^{-1})	Horizontal	Vertical	Multiplier
10^{-4}	87	133	×1.5
10^{-5}	207	428	×2.1
10^{-6}	564	428	×2.4
10^{-7}	1,740	4,280	×2.5

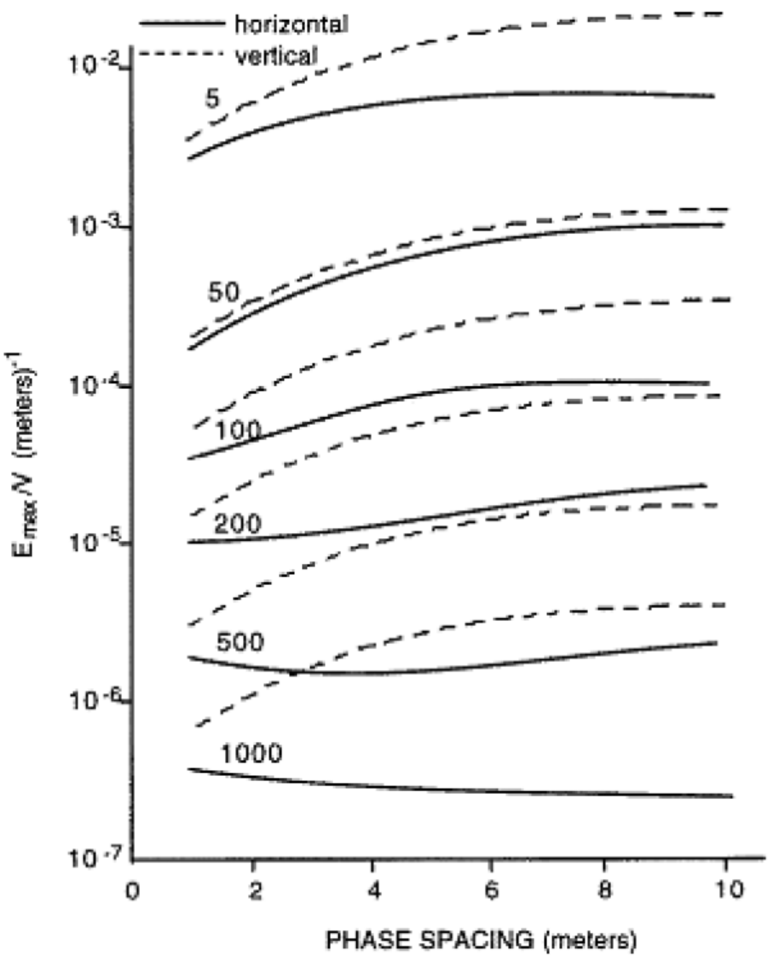

FIGURE 3. E_{max}/V vs. phase-spacing for horizontal and vertical lines (b = 0.001 m, d = 15 m) at indicated lateral distances.

E_{max}/V increases with increasing phase-spacing for a horizontal line at points near the line, but is almost independent of phase-spacing beyond 500 meters (Figure 3). For the vertical line, E_{max}/V increases with phase-spacing at all distances. In all cases, E_{max}/V is greater for the vertical configuration.

The dependence of E_{max}/V on line height is shown in Figure 4 for a practical range of heights. Near the line, E_{max}/V of a horizontal line decreases with increasing height; but it increases almost linearly at more distant points. E_{max}/V of the corresponding vertical line is almost independent of height at distances greater than abut 50 meters. Although the situation is complex within the first 50 meters, at more distant points, E_{max}/V is greater for the vertical configuration for all practical line heights.

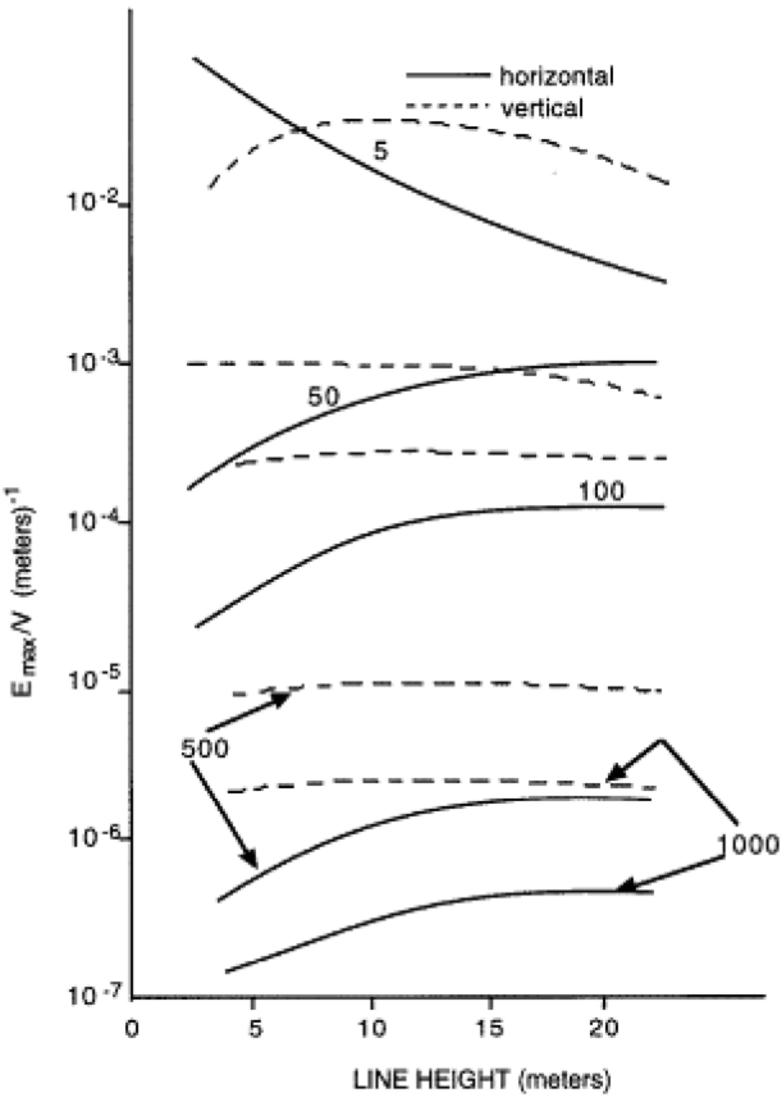

FIGURE 4. E_{max}/V vs. line height for horizontal and vertical lines (b = 0.001 m, c = 4 m) at indicated lateral distances.

For both lines, E_{max}/V increases with increasing cable diameter, but not significantly when compared to the other parameters considered. Within the range of practical cable diameters (0.5–5.0 cm) the variation of E_{max}/V is about 20%.

In summary, at distant points, E_{max}/V of a vertical line is greater than that of the equivalent horizontal line; the difference increases with distance. For a vertical line, the maximum field increases with phase-spacing and is almost independent of line height for the practical range of heights. E_{max}/V changes relatively little when the cable diameter is varied within a practical range of values. For a horizontal line, E_{max}/V increases with increased phase-spacing near the line, but is nearly independent of phase-spacing beyond 500 meters; the field also increases with line height. For almost all conditions, the electric field beyond about 50 meters is considerably lower for the horizontal configuration.

APPENDIX I

The potential V_i at the surface of each conductor in a 3-phase array can be expressed as

$$V_1 = Q_1C_1 + Q_2C_2 + Q_3C_3$$
$$V_2 = Q_1C_4 + Q_2C_5 + Q_3C_6$$
$$V_3 = Q_1C_7 + Q_2C_8 + Q_3C_9,$$

Where the Q_i are the charge densities on each conductor and the C_i are constants dependent on the geometry of the array (due to symmetry, there may be fewer than 9 independent constants).

It can be shown that the ground-level electric field is (1):

$$E = (1/2\,\pi\varepsilon_0)(Q_1d_1/r_1^2 + Q_2d_2/r_2^2 + Q_3d_3/r_3^2),$$

Where r_i is the distance to the ith conductor, d_i its height, and ε_0 is the permittivity of free space. If we define the phase relation as

$$V_1 = V\cos\omega t$$
$$V_2 = V\cos(\omega t + 2\pi/3)$$
$$V_3 = V\cos(\omega t - 2\pi/3),$$

where V is the peak voltage to ground, it can be shown that

$$E = A\cos\omega t + B\sin\omega t,$$

where A and B are constants dependent on the line geometry, operating voltage, and distance from the center-line;

$$A = A_1/r_1^2 + A_2/r_2^2 + A_3/r_3^2$$
$$B = B_1/r_1^2 + B_2/r_2^2 + B_3/r_3^2.$$

A_i and B_i are functions of V and C_i, and can be determined for any particular configuration by the method of images (1);

$$A_1 = d_1 K[C_5C_9 - C_6C_8 - 0.5C_3(C_8 - C_5) - 0.5C_2(C_6 - C_9)]$$
$$A_2 = d_2 K[C_6C_7 - C_4C_9 - 0.5C_1(C_9 - C_6) - 0.5C_3(C_4 - C_7)]$$
$$A_3 = d_3 K[C_4C_8 - C_5C_7 - 0.5C_2(C_7 - C_4) - 0.5C_1(C_5 - C_8)]$$

$$B_1 = 0.866 d_1 K[C_2(C_6 + C_9) - C_3(C_5 + C_8)]$$
$$B_2 = 0.866 d_2 K[C_3(C_4 + C_7) - C_1(C_6 + C_9)]$$
$$B_3 = 0.866 d_3 K[C_1(C_5 + C_8) - C_2(C_4 + C_7)]$$

$$K = V/\pi\varepsilon_0 C_{10}$$

$$C_{10} = C_1(C_5C_9 - C_6C_8) - C_2(C_4C_9 - C_6C_7) + C_3(C_4C_8 - C_5C_7)$$

The results for the lines shown in Figure 1 are listed below.

For a vertical line: $r_1^2 = x^2 + (d-c)^2$; $r_2^2 = x^2 + d^2$; $r_3^2 = x^2 + (d+c)^2$; $d_1 = d - c$; $d_2 = d$; $d_3 = d + c$. $\kappa = 1/2\pi\varepsilon_0$; $C_1 = \kappa \ln[2(d-c)/b]$; $C_2 = \kappa \ln[(2d-c)/b]$; $C_3 = \kappa \ln(d/c)$; $C_4 = C_2$; $C_5 = \kappa \ln(2d/b)$; $C_6 = \kappa \ln[(2d+c)/c]$; $C_7 = C_3$; $C_8 = C_6$; $C_9 = \kappa \ln[2(d+c)/b]$.

For a horizontal line: $r_1^2 = (x-c)^2 + d^2$; $r_2^2 = x^2 + d^2$; $r_3^2 = (x+c)^2 + d^2$; $d_1 = d_2 = d_3 = d$. $\kappa = 1/2\pi\varepsilon_0$; $C_1 = \kappa \ln(2d/b)$; $C_2 = \kappa \ln\left[(4d^2 + c^2)^{1/2}/c\right]$; $C_3 = \kappa \ln\left[(d^2 + c^2)^{1/2}/c\right]$; $C_4 = C_6 = C_8 = C_2$; $C_5 = C_9 = C_1$; $C_7 = C_3$.

The ground-level field at any distance from the center-line can be found by first computing the constants C_i for the line in question, and then finding $E(x)$. The maximum electric field is

$E_{max} = A\cos\phi + B\sin\phi$, $\phi = \tan^{-1}(B/A)$,

or $E_{max} = (A^2 + B^2)^{1/2}$.

REFERENCES

1. Hart, F.X. and Marino, A.A.: Energy flux along high-voltage transmission lines, IEEE Trans. Biomed. Eng., BME-24, 493–495, 1977.

2. Becker, R.O. and Marino, A.A.: Electromagnetism and Life, State University of New York Press, Albany, 1982.

3. Konig, H.L.: Biologic Effects of Environmental Electromagnetism, Springer-Verlag, Berlin, 1981.

4. Biological Effects of Extremely Low Frequency Electromagnetic Fields, Proceedings of the 18th Annual Hanford Life Sciences Symposium, 1978, US Department of Energy, Washington, DC.

5. Hamer, J.R.: Effects of low-level low-frequency electric fields on human reaction time, Commun. Behav. Biol., Part A 2, 217–221, 1968.

6. Wever, R.: Influence of electric fields on some parameters of circadian rhythms in man, in Biochronometry, M. Menaker, ed., National Academy of Science (USA), Washington, D.C., 117–132, 1971.

7. Beischer, D.E., Grissett, J.D., and Mitchel, R.E.: Exposure of Man to Magnetic Fields Alternating at Extremely Low Frequency, Naval Aerospace Medical Research Laboratory, NAMRL-1 180, Pensacola, Florida, 1973.

8. Wertheimer, N. and Leeper, E.: Electrical wiring configurations and childhood cancer, Am. I. Epidemiol., 109, 273–284, 1979.

9. Perry, F.S., Reichmanis, M., Marino, A.A., and Becker, R.O.: Environmental power-frequency magnetic fields and suicide, Health Physics, 41 267–277, 1981.

10. Milham, S.: Mortality from leukemia in workers exposed to electrical or magnetic fields, N. Engl. J. Med., 304, 249, 1982.