Magnetic Field Management for Overhead Transmission Lines: A Primer

Definitions, Methods of Performing Calculations, Field Management Options, and Other Issues

TR-103328
Research Projects 2472-06, 3959-02

Final Report, December 1994

Prepared by
GENERAL ELECTRIC COMPANY
EPRI High Voltage Transmission Research Center
115 East New Lenox Road
Lenox, Massachusetts 01240
Principal Investigator
L. Zaffanella

Prepared for
Duquesne Light Company
311 Grant Street
Pittsburgh, Pennsylvania 15279

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
R. J. Lordan

Environmental and Health Business Unit
Strategic Development Group

Transmission Lines Business Unit
Power Delivery Group

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS REPORT

GENERAL ELECTRIC COMPANY

ORDERING INFORMATION

Requests for copies of this report should be directed to the EPRI Distribution Center, 207 Coggins Drive, P.O. Box 23205, Pleasant Hill, CA 94523, (510) 934-4212.

REPORT SUMMARY

For nearly 25 years, research has addressed the issue of whether electric and magnetic fields from power lines and other sources might affect the health of exposed individuals. This informative, easy-to-use primer provides a primary source of basic information on the characteristics, measurement, and management of magnetic fields associated with overhead transmission lines. Technical personnel will be particularly interested in the document's comprehensive, tutorial approach.

Background
Though significant material is now available on overhead transmission line magnetic fields, it was not accessible in a convenient form and in a single document. This material includes information on the sources of transmission line magnetic fields, characterization of the sources–both spatially and temporally–and available magnetic field management options. As utility and other personnel became involved in this subject, the need for a tutorial document grew. The response to an earlier version of this primer, published for Duquesne Light and EPRI, suggested that a broader circulation of the material was appropriate.

Objective
To publish a primer providing an overview of information and concepts related to overhead transmission line magnetic field management.

Approach
Investigators from the EPRI High Voltage Transmission Research Center (HVTRC) prepared an overview of the characteristics, measurement, calculation, and management of magnetic fields from overhead transmission lines. They developed the primer by integrating available information in a logical and easy-to-use format.

Results
This primer provides an introduction to overhead transmission line magnetic fields. Specifically, the primer characterizes magnetic fields, with a look at such fundamental principles as units of measurement, direction in space, variations with time, and maximum allowable fields. A discussion of overhead transmission line magnetic fields focuses on spatial uniformity in residences, temporal stability, harmonic content, field orientation, and transients. A section on measurement and calculation techniques provides example calculations and explains the effect of overhead ground wires. Particularly pertinent to utilities is a description of which field characteristics may be

important such as cumulative field strength, the frequency of excursions, and the number of intermittents and transients. A comparison of exposure from different sources addresses areas such as transmission lines, electrical appliances, residential grounding systems, house wiring, and power distribution lines. Finally, a comprehensive look at magnetic field management identifies issues such as modification of activity patterns, design of electrical facilities and equipment to produce lower magnetic fields, and shielding.

EPRI Perspective

This primer compiles information on the characteristics, measurement, and management of transmission line magnetic fields in an easy-to-mad single volume. It is the first of a series of handbooks planned on transmission line magnetic field management. EPRI is currently finalizing one handbook of low-field design options for transmission lines as well as another on managing transmission line magnetic fields using active and passive wire loops.

TR-103328

Interest Categories

Electric and magnetic fields
Overhead electrical transmission

Keywords

Electric fields
Magnetic fields
Shielding
Overhead transmission

.

ABSTRACT

This Primer is in response to the contemporary interest in magnetic fields from electric power transmission lines.

The Primer presents definitions of magnetic field quantities, describes methods for magnetic field calculations, and discusses magnetic field management options.

The audience of this Primer are technical personnel of Electric Utilities or other organizations involved in the issue of magnetic field from power lines.

CONTENTS

1

TRANSMISSION LINE MAGNETIC FIELDS

Introduction

Since about 1970, research has addressed the issue of whether electric and magnetic fields from power lines and other sources might affect the health of exposed individuals.

Prior to about 1982 the focus was on electric fields, particularly of extra high voltage (EHV) transmission lines and substations, since these installations have the highest electric fields (two orders of magnitude or more larger than typical electric fields in residential environments).

Following a considerably large worldwide research effort on possible effects of power frequency electric fields, the general consensus of the scientific community today is that there are no demonstrable health effects of exposure to transmission line electric fields.

It should be noted that these fields do lead to spark discharges and to induced power frequency currents between people and objects. One of the design criteria of EHV transmission lines is the limitation of electrically induced currents below the let-go value for the worst case of a contact with the largest possible vehicle and the minimum clearances. A current above the "let-go" value could contract the body muscles and prevent the let-go of a hand grip.

With the publication of results of several epidemiologic studies, interest has shifted from electric fields to magnetic fields. Proximity to overhead power lines is a parameter often used in these epidemiologic studies. Interestingly, magnetic fields of comparable (or higher) strength to those from transmission and distribution lines can be produced by many sources, including some located in residential environments.

Three epidemiological studies (Wertheimer (1), Savitz (2), London (3)) have shown a correlation between childhood leukemia and overhead power line configurations near residences. Transmission lines (overhead power lines with voltages of 69 kV or greater) did not play a significant role and their exclusion would not have altered the conclusions of these studies. However, a Swedish study (4) specifically addressing overhead high voltage transmission lines found a correlation between childhood leukemia and proximity to the lines and to calculated yearly average exposure to power frequency magnetic field levels from transmission lines.

The issue of whether or not magnetic fields cause health effects has not been resolved. Research continues in an effort to clarify this issue.

MAGNETIC FIELD CHARACTERIZATION

We live in an "electromagnetic" environment whose sources are both natural (earth's magnetic field, lightning, sunlight) and man made. One of the man made sources of electric and magnetic fields is the electric power system.

EMF (Electric and Magnetic Fields)

Electric and magnetic fields are generated by the combination of electrical charges (voltage) and movement of electrical charges (electric currents). When the rate of change (frequency) of these fields is sufficiently low, as for power system fields, EMF can be separated into electric (related to voltages) and magnetic (related to current) fields. In this case, the word EMF should be defined as "Electric and Magnetic Fields", as opposed to "Electromagnetic." Electromagnetic fields refer to electric and magnetic fields that are coupled, as in high frequency radiating fields.

There is a spectrum of frequencies of electromagnetic fields. The product of frequency and wavelength of electromagnetic radiation equals the speed of light, 3×10^8 m/s. The wavelength associated with 60 Hz is 5000 km. By comparison, the wavelength of television transmission at 10^8 Hz is 3 m. When the distance from the source is large compared to the wavelength, electric and magnetic field are linked and considering them together is justified. However, when the distance from the source is small, such as in the case of magnetic field near transmission lines, the fields are independent and should be considered separately as electric and magnetic fields, not electromagnetic fields or radiation.

What Is A Magnetic Field?

Magnetic field is defined by the magnitude and direction of the force exerted on a moving charge.

If an electrical charge is moving into a magnetic field, or if a field moves past the charge, the charge will be subjected to a force.

If the unit electrical charge, one coulomb in the present international system (SI), moves at a unit velocity, i.e. one meter per second (SI), perpendicular to a magnetic field of a unit flux density, i.e. one tesla (SI), it will be subjected to a unit force, i.e. one newton (SI), in a direction orthogonal to both the direction of the charge motion and the direction of the magnetic field.

The quantity described is the magnetic flux density, which, in a region with magnetic flux, is the magnetic flux in the unit of area perpendicularly traversed by the flux.

The above definition, although correct, is not very intuitive. To gain better physical insight into the meaning of magnetic flux density, consider a single long wire carrying a current, I. The magnetic flux density in the surrounding air at a distance, R from the wire is equal to 2×10^{-7} I/R tesla. For instance, if the wire carries 1 ampere, at the distance of 1 meter, the magnetic flux density is equal to 2×10^{-7} tesla. The magnetic flux density is a vector quantity (has a direction and magnitude in space) which, in this example, is tangential to the circle with radius R.

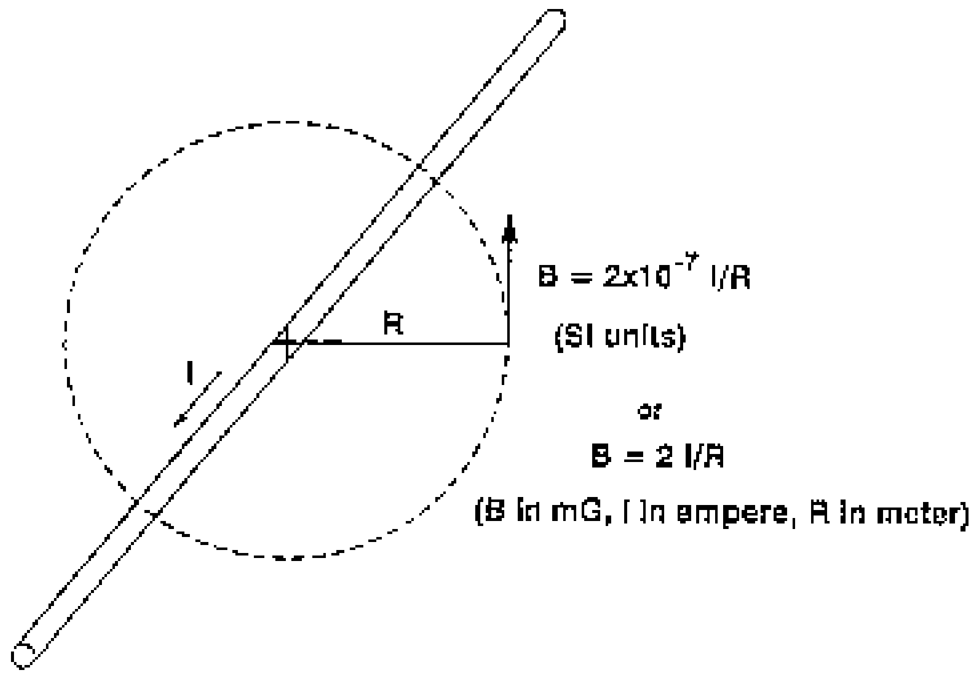


Figure 1
Magnetic Flux Density Outside an Infinitely Long Current-Carrying Wire

Units of Measurements

When engineers talk about a magnetic field, they refer to the "magnetic flux density", which is often indicated using the letter B. The magnetic flux density B is the flux per unit area.

$\phi = B\,A$ (weber)

The unit of A is meter^2. The unit or B is weber/meter^2, or tesla.

It is important to note that there is also a "magnetic field strength", usually indicated using the letter H. In SI units, the magnetic flux density B is measured in tesla (T) and the magnetic field strength is measured in ampere per meter (A/m). B and H are related to each other through the permeability of the medium, indicated by the symbol ?. (Greek letter mu).

$$B=\mu H$$

The permeability, μ, is a material characteristic which gives an indication of how that material affects the magnetic flux density that penetrates it. The permeability of vacuum, air and biological matter is nearly the same: $\mu = \mu_o$.

If B is expressed in tesla and H in ampere/meter, then $\mu_o = 4.\pi.\ 10^{-7} = 1.257.10^{-6}$. The SI unit for the permeability, μ, is henry/meter (H/m). The magnetic flux through a surface is obtained by multiplying the flux density by the area of the surface. The unit of flux is the weber (Wb). One tesla is equal to one weber per square meter (Wb/m^2). Generally, when we talk about magnetic field we mean the magnetic flux density.

As mentioned, the SI unit for magnetic flux density is the tesla (T). The unit commonly used in the United States is the gauss (G);which is the magnetic flux density expressed in Wb/cm^2.

$$1G = 0.0001T = 10^{-4}T$$

However, since most magnetic fields experienced by people are much lower than one gauss, a more commonly used unit is the milligauss (mG).

$$1mG = 0.001G = 10^{-7}\ T = 0.1\mu T$$

European publications quite often use the term microtesla (μT); one microtesla is equal to 10^{-6} tesla or 10 milligauss.

Direction In Space

The magnetic field at a point in space and at a given moment in time (i.e. its instantaneous value) is characterized by a magnitude and a direction. This instantaneous value, b, can be expressed by a vector in space. This vector can be described by its components along the three axes of an orthogonal coordinate system.

$$\overline{b} = b_x\overline{u}_x + b_y\overline{u}_y + b_z\overline{u}_z$$

where the bar over a quantity indicates a vector; $\bar{u}_x$, $\bar{u}_y$, $\bar{u}_z$ represent the unit vectors in the x,

y, and z directions, respectively; b_x, b_y, b_z are the magnitudes of the three space components of the magnetic field along the x, y, and z axes, respectively.

The magnitude of the instantaneous value of the field is related to the magnitudes of the three orthogonal space components by:

$$b = \sqrt{b_x^2 + b_y^2 + b_z^2}$$

The angle in space is also defined by the three orthogonal space components and can be expressed using appropriate trigonometric functions.

Variations With Time

The magnetic field generated by the power system at a point in space is not constant in time for a variety of reasons. For instance, most power systems operate with AC currents, which vary periodically at the power frequency. The dominant power frequency in the US is 60 Hz (60 cycles per second). Therefore, the magnetic field changes magnitude, or direction (or both), every one sixtieth of a second (0.0167 s).

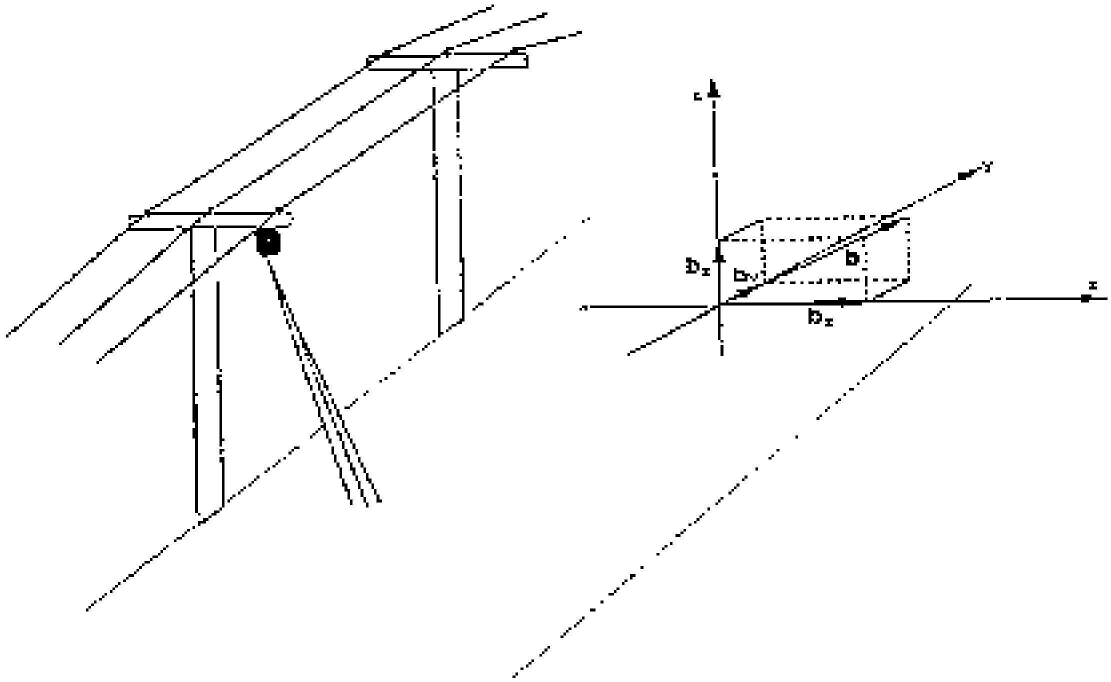


Figure 2
Magnetic Field: A Vector Which Varies in Time

In the most general case, all of the three orthogonal components vary with time and can be expressed as functions of time. The field at a point in space is then also a function of time.

$$\overline{b}(t) = b_x(t)\overline{u}_x + b_y(t)\overline{u}_y + b_z(t)\overline{u}_z$$

For the magnetic field generated by an AC power system, the magnetic fields $b_x(t)$, $b_y(t)$, and $b_z(t)$ are periodic functions of time, and each can be expressed as the sum of sinusoidal magnetic fields at the power frequency and at its harmonics (a harmonic field has sinusoidal variations with a frequency multiple of the power frequency), e.g.:

$$b_x(t) = \sqrt{2}B_{x1}\sin(\omega t + \alpha_{x1}) + \sqrt{2}B_{x2}\sin(2\omega t + \alpha_{x2}) + \ldots\sqrt{2}B_{xn}\sin(n\omega t + \alpha_{xn}) + ..$$

where $\sqrt{2}\ B_{xn}$ and α_{xn} are the amplitude and the phase angle of the n^{th} harmonic of the magnetic field component along the x axis, and $\omega = 2\pi f$ with f being the power frequency (e.g. 60 Hz).

60 Hz Magnetic Fields

Most magnetic fields generated by the power system, particularly those from transmission lines, have a dominant component at 60 Hz with negligible harmonics. The three orthogonal space components of the magnetic field are sinusoidal functions at 60 Hz**:**

$$b(t) = \sqrt{2}B_x \sin(\omega t + \alpha_x) \cdot \overline{\mu}_x + \sqrt{2}B_y \sin(\omega t + \alpha_y) \cdot \overline{\mu}_y + \sqrt{2}B_z \sin(\omega t + \alpha_z) + \cdot \overline{\mu}_z$$

with $\omega = 2 \pi 60 = 377$ for 60 Hz.

Let's imagine the vector $\overline{b}$ as an arrow anchored at the point where the magnetic field is measured, with a length proportional to the value b, and a direction determined by the relative magnitudes of the three orthogonal components. The arrow will be seen moving with time. Every 1/60th of a second, the tip of the arrow will describe a simple pattern: for the most general case this will be an ellipse.

The ellipse can be characterized by its major and minor axes. When the major and minor axes are equal in magnitude, the ellipse becomes a circle; in this case, the field b is constant in magnitude, but its direction varies with time. On the other hand, when the minor axes becomes very small with respect to the major axis, the ellipse becomes very narrow, until it eventually collapses into an oscillating vector; in this case, the field is represented by a space vector which has a constant direction, but a magnitude which varies with time.

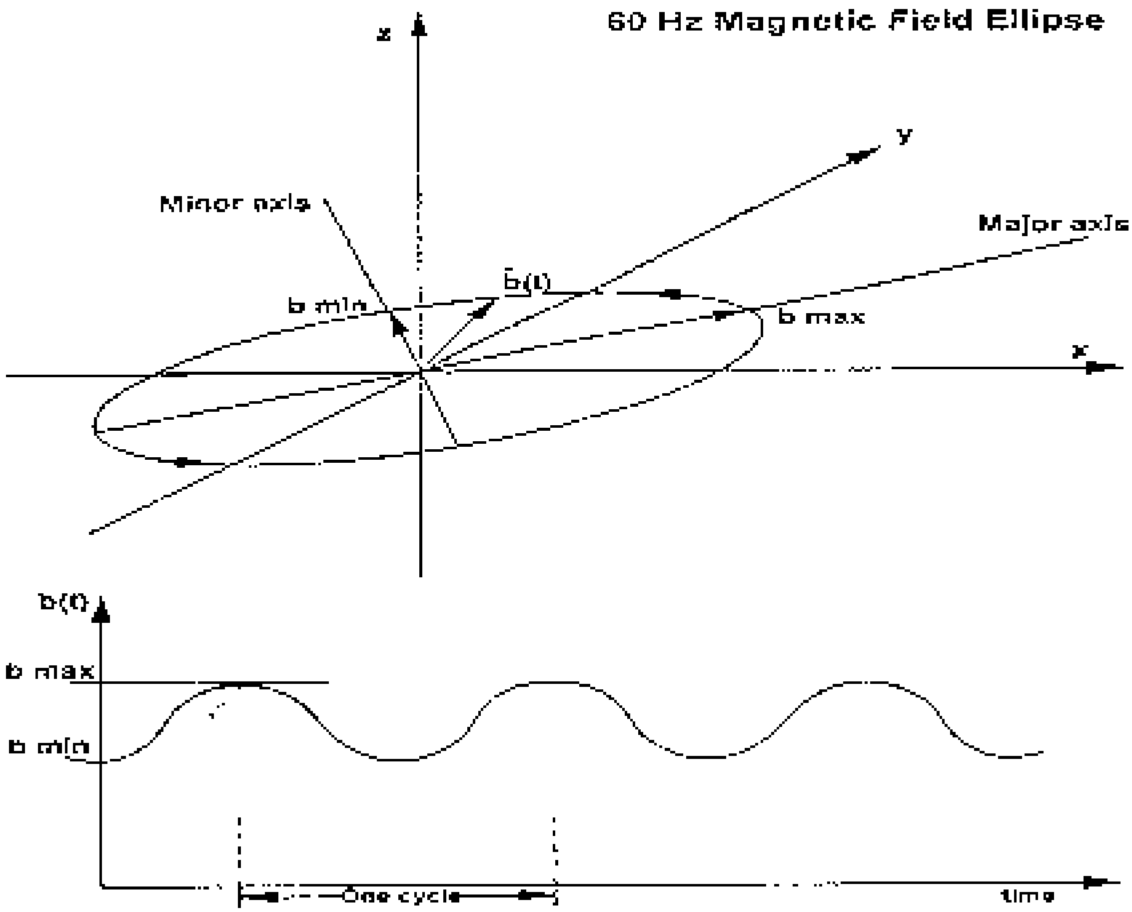


Figure 3
60 Hz Magnetic Field Ellipse and Variation of Magnetic Field With Time

When the field vector has a constant direction in space, we say that the field is linearly polarized. This occurs, for instance, when all the 60 Hz currents that cause the magnetic field are in phase with each other such as in a single-phase distribution line composed of a primary wire and a neutral that carries the return current. A linearly polarized field may also be found in three-phase systems for some conductor arrangements. If the field vector describes an ellipse, the field is elliptically polarized. A system of 60 Hz currents not in phase with each other, such as most three-phase transmission and distribution lines, will, in general, generate elliptically polarized fields. The degree of polarization is defined by the axial ratio, which is the ratio between the minor and the major axes of the ellipse.

Degree of polarization = axial ratio = b_{min}/b_{max}

The axial ratio can range from zero to one. When the axial ratio is equal to zero, the field is linearly polarized. When the axial ratio is equal to one, the field is circularly polarized.

RMS Value

The r.m.s. (root mean square) value of the magnetic field is used to characterize the intensity of the field, despite its complicated variations in space and time. In mathematical terms, the r.m.s. value can be derived from the function expressing the amplitude of the magnetic field vector versus time as follows:

$$B_{rms} = \frac{1}{T}[b(t)]^2 dt$$

where the variable t is the time, and T is equal to one period of the time function (e.g. 1/60 s).

It can be shown that the r.m.s. value of the field has simple relationships with three orthogonal space components:

$$B_{rms} = \sqrt{B_x^2 + B_y^2 + B_z^2}$$

B_x, B_y, B_z are the r.m.s. values of the time varying components $b_x(t)$, $b_y(t)$, $b_z(t)$ along three orthogonal axes. The above equation is valid no matter what the periodic time functions are, i.e., it is valid also if the 60 Hz field is not purely sinusoidal, but contains harmonics of the power frequency.

If the magnetic field contains harmonics of the power frequency, the field can be seen as the combination of different sinusoidal fields each one at a different frequency: 60 Hz, 120 Hz (second harmonic), 180 Hz (third harmonic), etc. The r.m.s. value of the magnetic field is equal to the square root of the sum of the squares of its harmonic components:

$$B_{rms} = \sqrt{B^2_{rms,60} + B^2_{rms,120} + B^2_{rms,180} + ..etc.}$$

with

$$B_{rms,60} = \sqrt{B^2_{x,60} + B^2_{y,60} + B^2_{z,60}}$$

$$B_{rms,120} = \sqrt{B^2_{x,120} + B^2_{y,120} + B^2_{z,120}}$$

and so on.

At each frequency the r.m.s. value can also be obtained also from the r.m.s. values of the field components measured along the two axes of the magnetic field ellipse:

$$B_{rms} = \sqrt{B_{\max}^2 + B_{\min}^2}$$

where B_{max} is the r.m.s. value of the field measured in the direction of the major axis of the field ellipse, expressed by the time function:

$$b_{major}(t) = b_{\max} \cdot \cos(\omega t + \varphi_m)$$

This function has an r.m.s. value $B_{\max} = \frac{b_{\max}}{\sqrt{2}}$

Resultant

Sometimes the square root of the sum of the values of three orthogonal components is referred to as the magnetic field "resultant". If the values of the three orthogonal components are rm.s. values, then the resultant field coincides with the r.m.s. field.

Maximum Field

While biologists may prefer the use of B_{rms}, the early instrumentation for measurements of 60 Hz magnetic fields has promoted the use of B_{max} in measurements standards and magnetic field guidelines. The maximum 60 Hz field, B_{max}, is also an r.m.s. value. It is, in fact, the r.m.s. value of the 60 Hz field measured in the direction along which this value is maximum.

The distinction between maximum field, B_{max}, and r.m.s. field, B_{rms}, is important because these quantities are used in publications often without further qualifications other than calling either one of them the "field value". If the 60 Hz field is linearly polarized, the values of these two quantities coincide. However, if the field is elliptically polarized, the r.m.s. field value, B_{rms}, is larger than the maximum field value, Bmax. The largest discrepancy occurs when this field is circularly polarized ($B_{min} = B_{max}$), in which case $B_{rms} = \sqrt{2}\ B_{\max}$.

How To Measure Magnetic Fields

The simplest way to measure AC magnetic fields is to measure the field components alternatively along three perpendicular directions, using a meter connected to a single-axis probe, usually a wire coil. The AC magnetic field induces in the coil a voltage proportional to the rate of change of the magnetic field (V = k dB/dt).

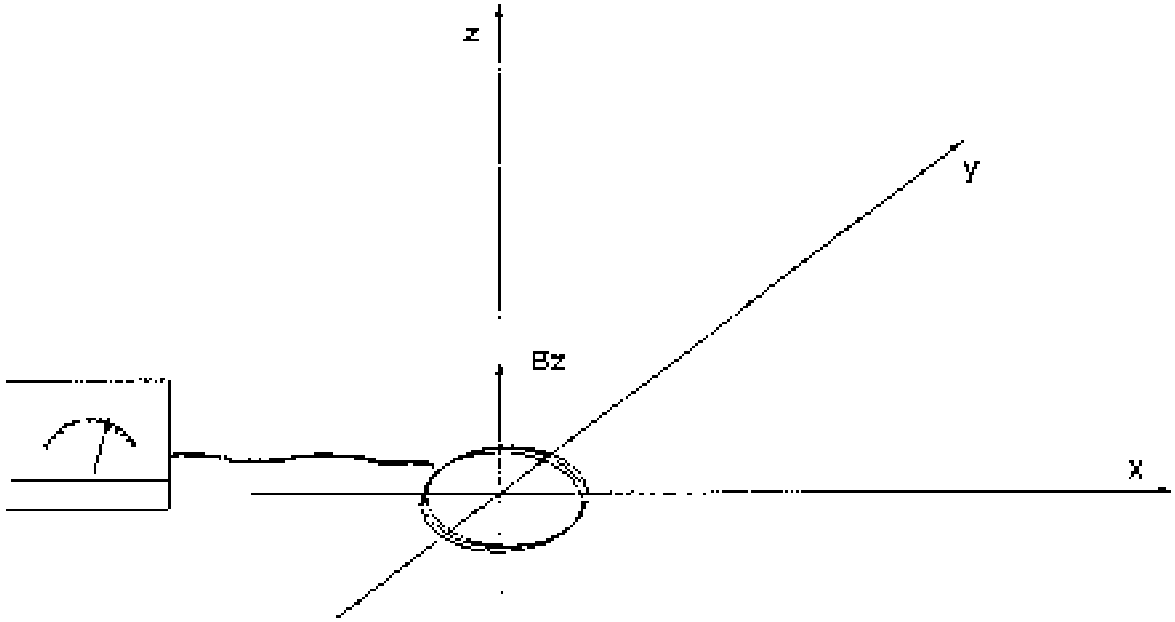


Figure 4
Single Axis Meter Measuring Magnetic Field in the Direction Perpendicular to the Plane of its Probe

Depending on their construction or calibration, magnetic field meters can read either total r.m.s. values (accounting for all harmonics), or the r.m.s. values of the 60 Hz component, or more complex quantities.

The resultant value of the field can be calculated from the measured values of three orthogonal components:

$$B_{res} = \sqrt{B_x^{\,2} + B_y^{\,2} + B_z^{\,2}}$$

If B_x, B_y, and B_z are r.m.s. values, then B_{res} is also an r.m.s. value.

By orienting the probe in different directions and searching for the maximum reading, the r.m.s. value in the direction of the major axis of the field ellipse is found. The direction of the minor axis is more difficult to find. One way to find the minor axis would be to place the plane of the probe parallel to the major axis and rotate the probe (maintaining the major axis in the plane of the probe) until the maximum reading is obtained.

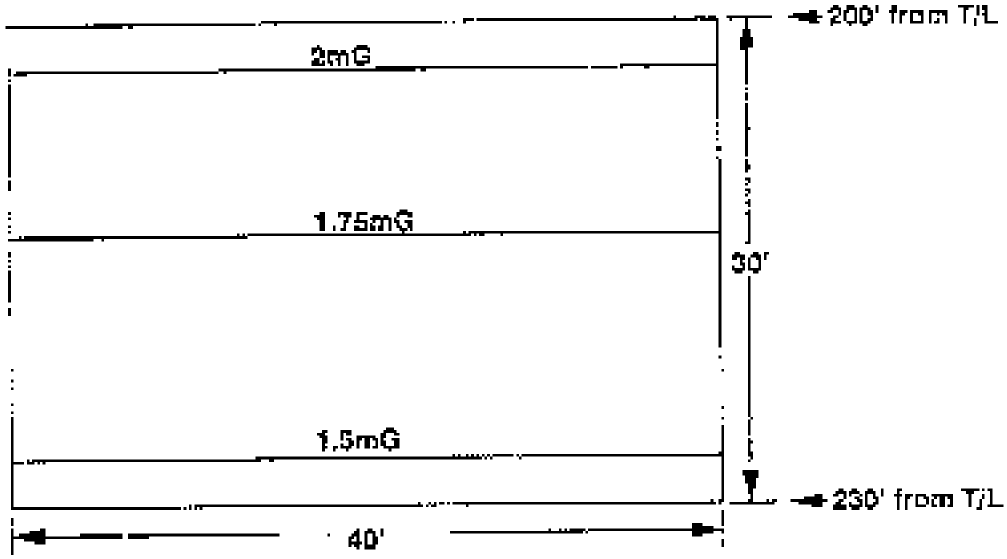
Today, many measurements are made with three-axis digital recorders. The values (total r.m.s., 60 Hz r.m.s., etc.) of the field components along three orthogonal axis are digitally recorded or displayed. Some meters can display directly the resultant values (total r.m.s. resultant, 60 Hz r.m.s. resultant, or other resultants). Others require calculations of the resultant values by taking the square root of the sum of the square of the three orthogonal components.

Most of the three-axis digital recorders do not measure phase angles nor the values of individual harmonics of the 60 Hz. These meters cannot give the values of the maximum field component (i.e., the component along the major axis of the ellipse, B_{max}) nor that along the minor axis of the ellipse, B_{min}, nor the degree of polarization (axial ratio). More sophisticated magnetic field measuring instruments are available that can provide a complete field characterization by recording the wave shapes of field components along three orthogonal directions.

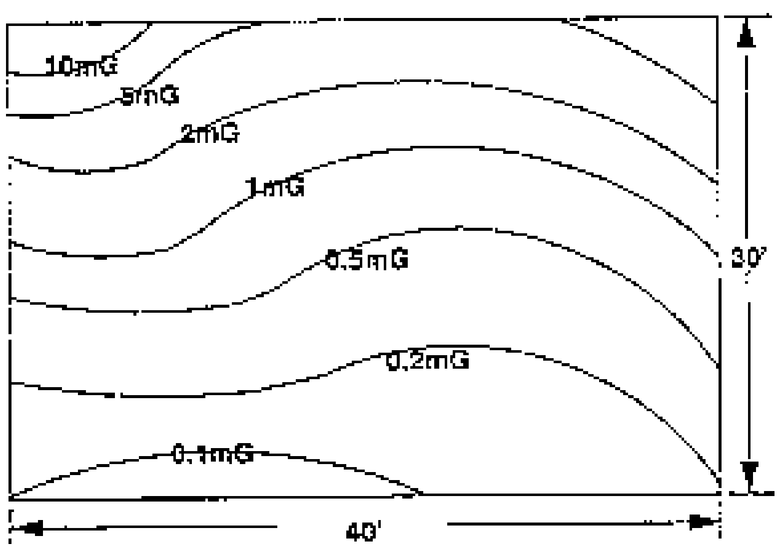
CHARACTERISTICS OF OVERHEAD TRANSMISSION LINE MAGNETIC FIELDS

In a modern society, power system magnetic fields are present in virtually every situation and come from a variety of sources. While overhead transmission lines' obvious visibility makes them a frequent target of public scrutiny, it is not clear whether community magnetic field exposure from overhead transmission lines is greater than from any other magnetic field source. We do not know how to define either exposure or dose in terms that relate to health effects, or even if a relationship exists. The characteristics of overhead transmission line magnetic fields are significantly different from those of other sources, as follows:

1. Spatial Uniformity In Residences. The magnetic field at locations near overhead transmission lines, such as in the right-of-way directly underneath the conductors, may reach tens or hundreds milligauss. These levels are typically greater than the magnetic field levels measured in most residential environments. Outside the fight-of-way, however, the magnetic field decreases rapidly going away from the line. The field generally decays in inverse proportion to the square of the distance from the line. Inside houses, even those near transmission corridors, the magnetic field from overhead transmission lines rarely exceeds 10 mG. The spatial distribution of transmission line fields is more uniform than that of any other common magnetic field source. For instance, the field caused by an overhead transmission line may differ by no more than 30% from one point to another inside the same residence. By contrast, the field caused by currents in the grounding system of a residence may vary by more than 100 to 1 and electrical appliance fields may vary from point to point inside a residence by more than 10,000 to 1.



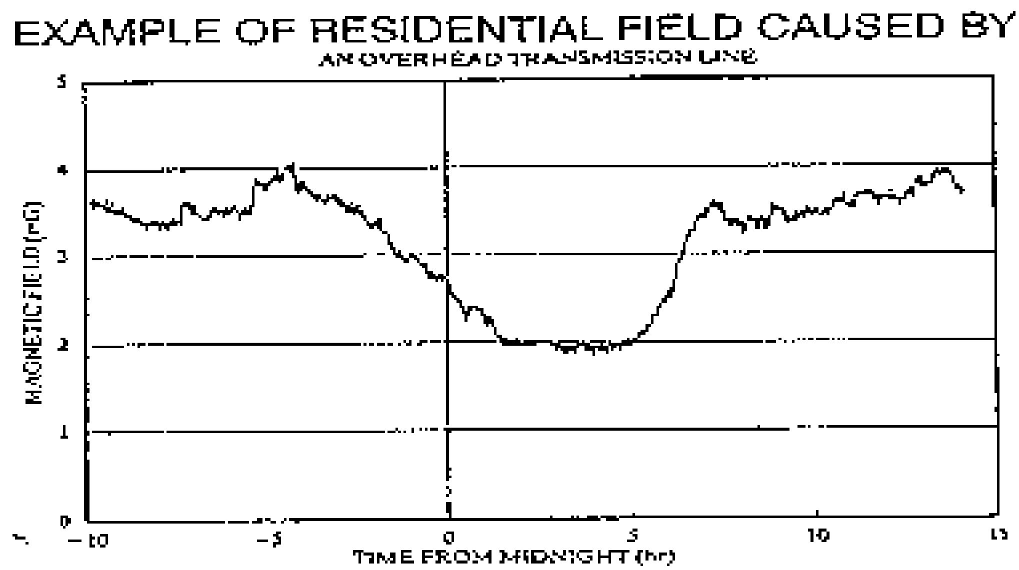
PLAN VIEW - MAGNETIC FIELD FROM A TRANSMISSION LINE
(EXAMPLE)



PLAN VIEW - MAGNETIC FIELD FROM GROUNDING SYSTEM
OF A RESIDENCE - *(EXAMPLE)*

Figure 5
Transmission Line Magnetic Field Inside Residences is More Uniform Than that of Other Sources

2. Temporal Stability Another characteristic of transmission line magnetic fields is their relatively small variation with time. Some transmission lines are constantly loaded, and their magnetic fields vary little with time. Some other lines have variable loads showing pronounced seasonal, weekly, and daily variations. Even the most variable transmission line loads, however, are not as variable as the loads of most other sources, such as electrical appliances, house wiring, and power distribution lines.



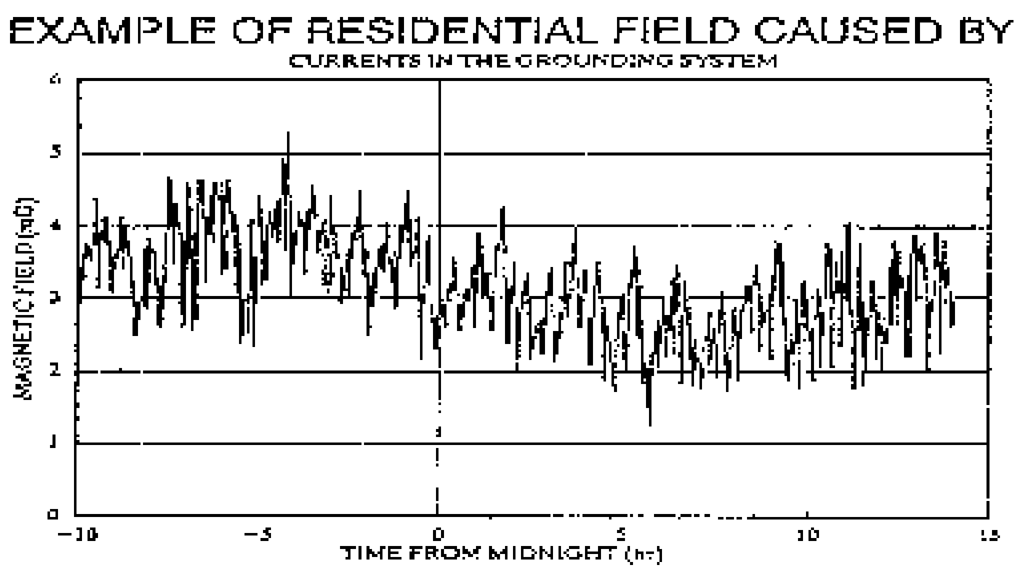


Figure 6
Transmission Line Magnetic Field Varies With Time Less Than Most Other Sources

3. Harmonic Content. Transmission line magnetic field is characterized by a relatively pure sinusoidal wave shape with little harmonic content. This, again, is in sharp contrast with other common sources whose magnetic field have a significant harmonic content. Table 1, based on measurements in or near residences, shows the differences between transmission line and other magnetic field sources vis-à-vis harmonic content.

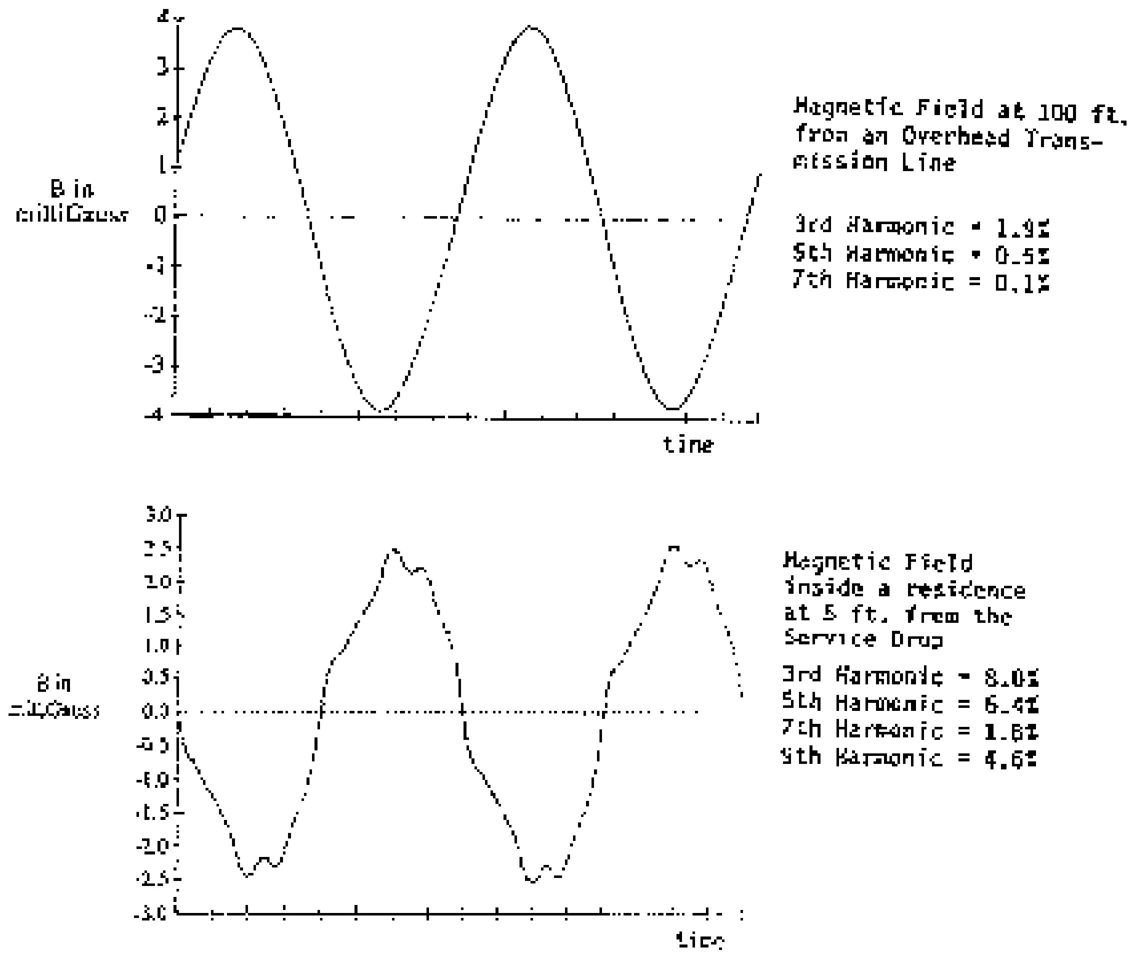


Figure 7
Wave Shape of Transmission Line Magnetic Field is More Sinusoidal Than That of Most Other Sources

Table 1
Harmonic Content Of Some Residential Magnetic Fields
Harmonic Amplitude Relative to 60HZ (%)
(Measurements performed by EPRI HVTRC)

Harmonic Order	2	3	4	5	7	9	11	13	15
Microwave	1-4	20-31	2-4	4-9	1-2	0.3-0.5	0.2-0.6	0-0.3	0-0.3
Refrigerator	0.7-1.3	5-8	0.3-0.6	0.5-3	0.3-2	0.1-1	0.1-0.5	0.1-0.2	<0.1
TV Set	17-42	12-25	9-17	7-13	4-9	4-5	2-4	1-2	1-2
Oven/Range	0.3-0.4	1-3	0.1-0.2	1-3	0.4-1	0.2-0.3	0-0.2	0-0.1	<0. 1
Clock Radio	0.2-7	1-23	0-5	0.4-14	0.1-8	0.1-3	0-3	0-1	0-0.5
Hair Dryer	70-120	11-15	5-7	4-9	5-6	4-8	2-4	1-6	1-4
Typewriter	3	65	1.2	19	3.3	2.7	2	0.8	0.3
Disk Drive	56	40	29	23	13	10	5.2	3.7	2.4
Copier	190	17	180	16	14	12	9	7	4
Fluorescent Light	1.1	56	0.6	7.2	8	3	0.9	1	0.3
Transmission Line (in P/W)	0. 1	0.5-0.9	0	0.6-1.3	0.2	0-0.1	0.1	<0.1	<0.1
Transmission Line (outside P/W)	0.2-1.4	0.5-3	0.1-0.4	0.5-1.1	0.1-0.3	0.1-0.3	0.1-0.2	0.1	0-0.1
Distribution Line (net current)	0.5-2	6-55	0.2-1.2	0.7-20	0.5-13	0.2-9	0-5	0-2	0-0.7
Grounding System of Houses	2-7	4-30	1.5-2.5	1.5-20	0.9-9	0.3-2	0.3-0.7	0.1-1	0-0.5

4. Field Orientation. The vector representing the magnetic field of an overhead transmission line lies in plane perpendicular to the line. There is no field component in the direction parallel to the line. The field may be elliptically polarized, i.e., the vector field may describe an ellipse. This depends on the geometry of the transmission line. For instance, three-phase lines with the three conductors in line with each other (flat or vertical arrangements) produce fields that, outside the right of way, are almost linearly polarized. Lines with triangular (delta) configuration produce elliptically polarized fields. When the configuration is an equilateral delta, the major and minor axes of the field ellipse are about equal producing a field with nearly circular polarization.

5. Transients. The current surges in overhead transmission lines that may cause magnetic field transients characterized by large rates of change of magnetic field, (dB/dt), are likely to be quite different (in shape and frequency of occurrence) from those generated by other sources of magnetic field.

HOW TO MEASURE TRANSMISSION LINE MAGNETIC FIELDS

Because of their properties, magnetic fields from overhead transmission lines are more simple to measure and to characterize than those from other sources of magnetic field exposure.

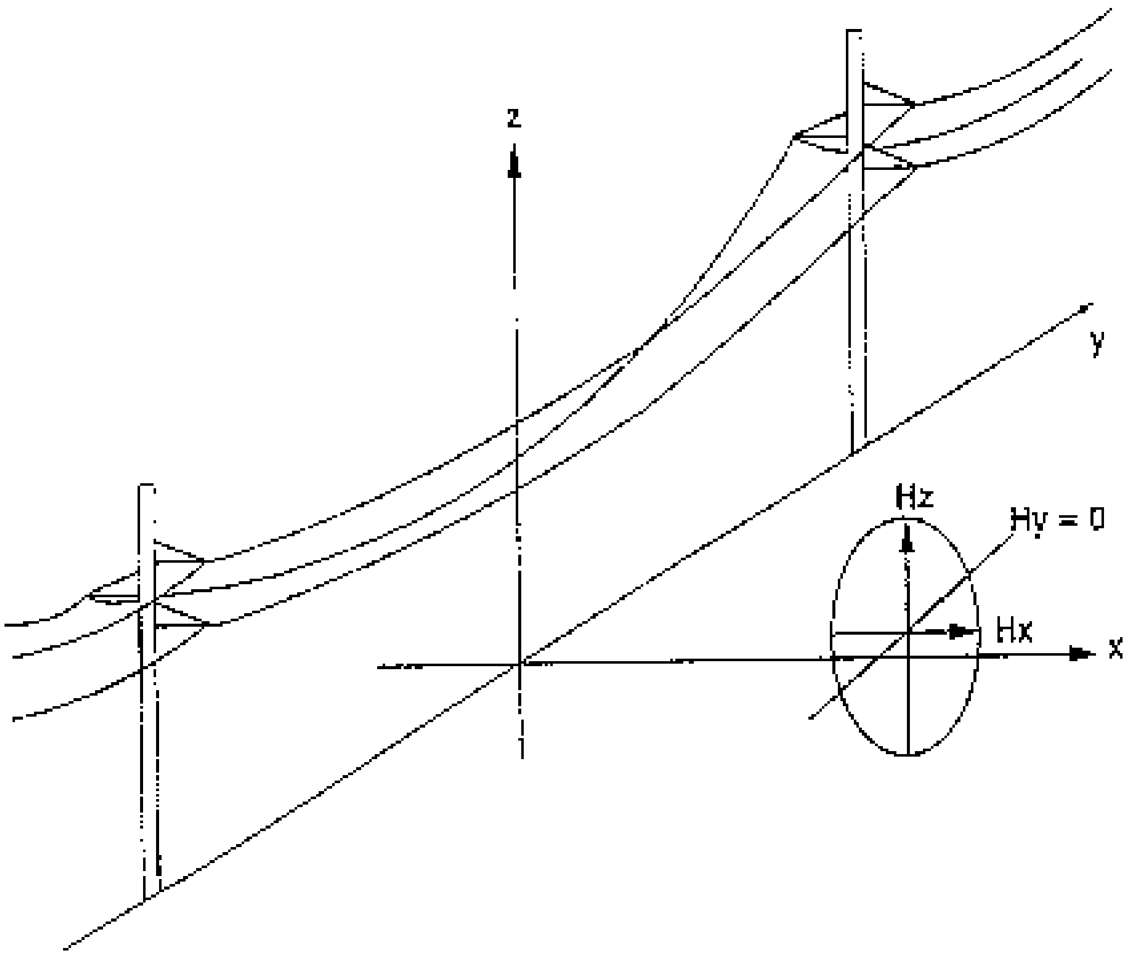


Figure 8
Magnetic Field of a Transmission Line Has Components Only in the Plane Perpendicular to the Line

Overhead transmission lines were the first source for which power system magnetic field measurement guidelines were established by the Institute of Electrical and Electronic Engineers (IEEE). These guidelines recommend to measure the fields with a calibrated single-axis field meter at one meter above ground. The probe is to be rotated until a maximum reading is obtained. The r.m.s. value is to be read from an analog or digital display.

Measurements can be made without concern that the field will be perturbed by the proximity of operator, vegetation, or most structures. However, measurements must be taken sufficiently away from objects made of steel or other ferromagnetic materials, which may distort the magnetic field. For instance magnetic field measurements should not be taken inside or near a vehicle. Additionally, underground facilities such as pipe lines or other buried metal objects may carry currents that could affect the magnetic field.

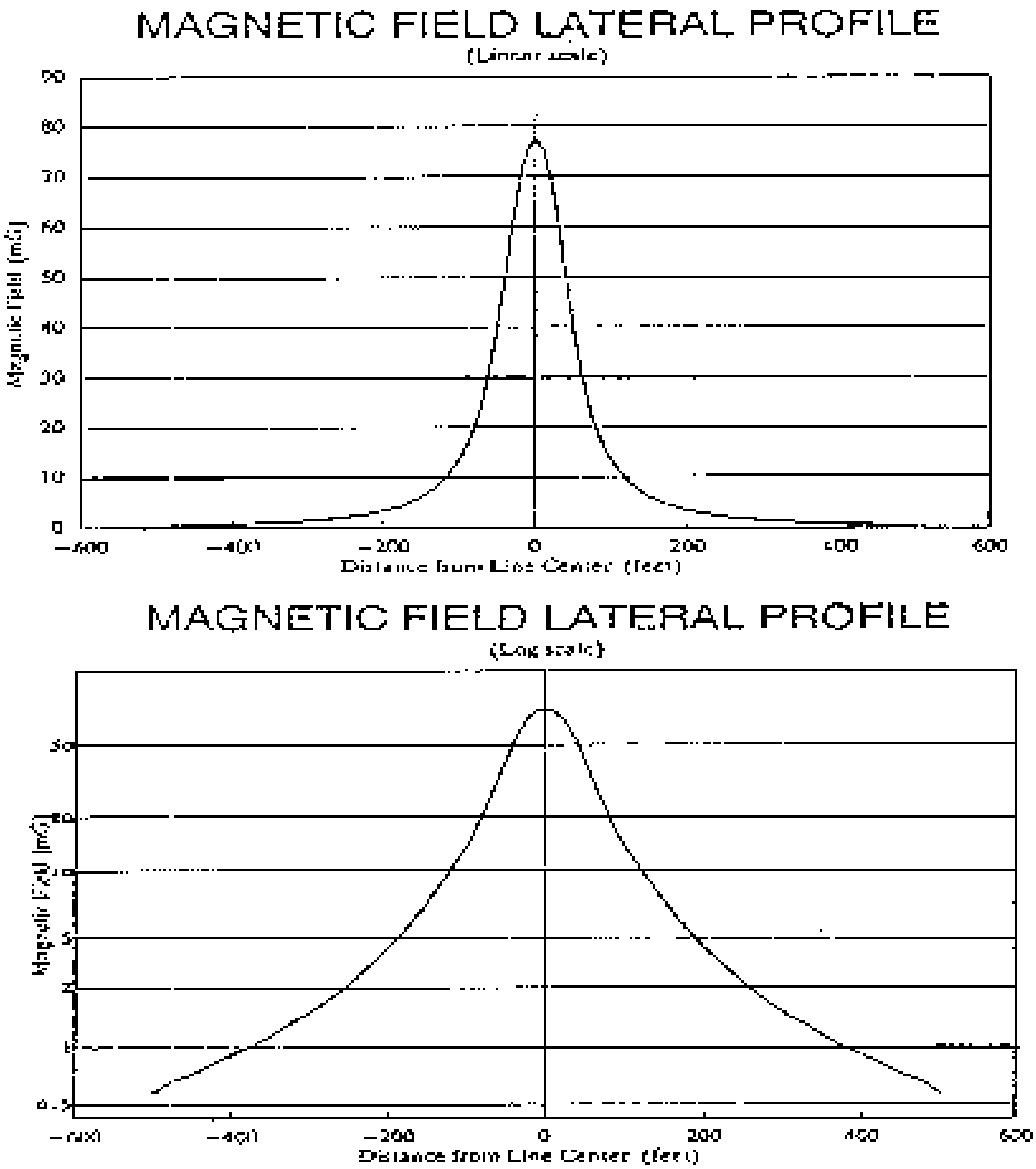


Figure 9
Transmission Line Magnetic Field Varies Rapidly with Distance from the Line

It is recommended that measurements of the magnetic field of a transmission line be made at midspan at different lateral distances from the line. These measurements can provide a so called "lateral profile" of the line magnetic field. Examples of such profiles can be easily found in the technical literature. When a linear scale is used, the difference between fields inside and outside the right-of-way is dramatically apparent. The use era logarithmic scale for the magnetic field may be more appropriate for an accurate assessment of the field far from the right-of-way.

Today, the most commonly used meters allow automated recordings of the horizontal and vertical components of the field along a path perpendicular to the line to provide the data for the lateral profile of the line magnetic field.

HOW TO CALCULATE TRANSMISSION LINE MAGNETIC FIELDS

Magnetic fields produced by transmission lines are generally calculated using computer programs such as the Electric Power Research Institute's ENVIRO program and the well known Bonneville Power Administration program. These programs are relatively simple to use and provide accurate prediction of the magnetic field if amplitude and phase angle of all the currents are known. These programs are applicable when the wires can be approximated as infinitely long conductors parallel to each other and to the ground. Conductor sag is ignored and the magnetic field lateral profile at midspan is calculated as if the conductors' vertical coordinates were constant and equal to those at midspan.

The equations used for the calculations are described in EPRI's Transmission Line Reference Book, second edition, pages 341-342. Transmission line field calculations provide the r.m.s. values of horizontal and vertical field components, B_x and B_z, the "maximum field" value, B_{max} (which is the r.m.s. value of the field measured in the direction along which the field is maximum), and the r.m.s. value of the resultant field, B_{rms} (which is the r.m.s. value of the magnitude of the field vector).

Example Calculations

As an example, let us calculate the magnetic field at 1 meter above ground, 100 ft (30.5 m) away from a three-phase line with all three phases at a height of 40 ft (12.2 m) above ground with a 30 ft (9.15 m) separation between phases. Let the currents of the three phases be equal to 1000 A and with a phase angle of 120^{o} from each other.

The currents can be represented using their real and imaginary parts. If the currents are given in terms of magnitude (I_A, I_B, I_C) and phase angles (z_A, z_B, z_C), the real and imaginary parts are calculated as follows:

Phase A, real part	$I_{A_r} = I_A \cdot \cos\varphi_A$
Phase A, imaginary part	$I_{A_i} = I_A \cdot \sin\varphi_A$
Phase B, real part	$I_{B_r} = I_B \cdot \cos\varphi_B$
Phase B, imaginary part	$I_{B_i} = I_B \cdot \sin\varphi_B$
Phase C, real part	$I_{C_r} = I_C \cdot \cos\varphi_C$
Phase C, imaginary part	$I_{C_i} = I_C \cdot \sin\varphi_C$

Table 2 shows these calculations, as well as the following step-by-step calculations made for the example of Figure 10.

Since the phase A current has a real and an imaginary part, the magnetic field produced by this current will also have a real and an imaginary part. The real part of the magnetic field, B_{Ar}, is caused by the real part of the phase A current, I_{Ar}, and is evaluated as indicated in Figure 1. B_{Ar} is perpendicular to the line connecting the measuring point, P, with phase A and has a value:

$$B_{A_r} = 2 \cdot 10^{-7}\left(\frac{I_{A_r}}{R_A}\right)$$

The field, B_{Ar}, can be divided into a vertical and a horizontal component. The vertical component, B_{Ar}, is the projection of B_{Ar} into a vertical line (z axis of Figure 10):

$$B_{A_{z_r}} = B_{A_r} \cdot \cos\alpha = B_{A_r} \cdot \frac{L_A}{R_A} = 2 \cdot 10^{-7} I_{A_r}\left(\frac{L_A}{R_A}\right)^2$$

The horizontal component, B_{Axr}, is the projection of B_{Ar} into the horizontal (x axis if Figure 10):

$$B_{A_{x_r}} = B_{A_r} \cdot \sin\alpha = B_{A_r} \cdot \frac{H_A}{R_A} = 2 \cdot 10^{-7} I_{A_r}\left(\frac{H_A}{R_A}\right)^2$$

It should be noted that there is no field component in the direction parallel to the transmission line ($B_{Ayr} = 0$, $B_{Ayi} = 0$).

The same operations are repeated for the imaginary vertical, B_{Azi}, and the imaginary horizontal, B_{Axi}, components of the magnetic field caused by phase A and then for the other two phases. For each phase there will be a real vertical, a real horizontal, an imaginary vertical, and an imaginary horizontal field component.

The real parts of the horizontal components of all the phases are added. The result is the real part of the horizontal component of the magnetic field caused by the transmission line.

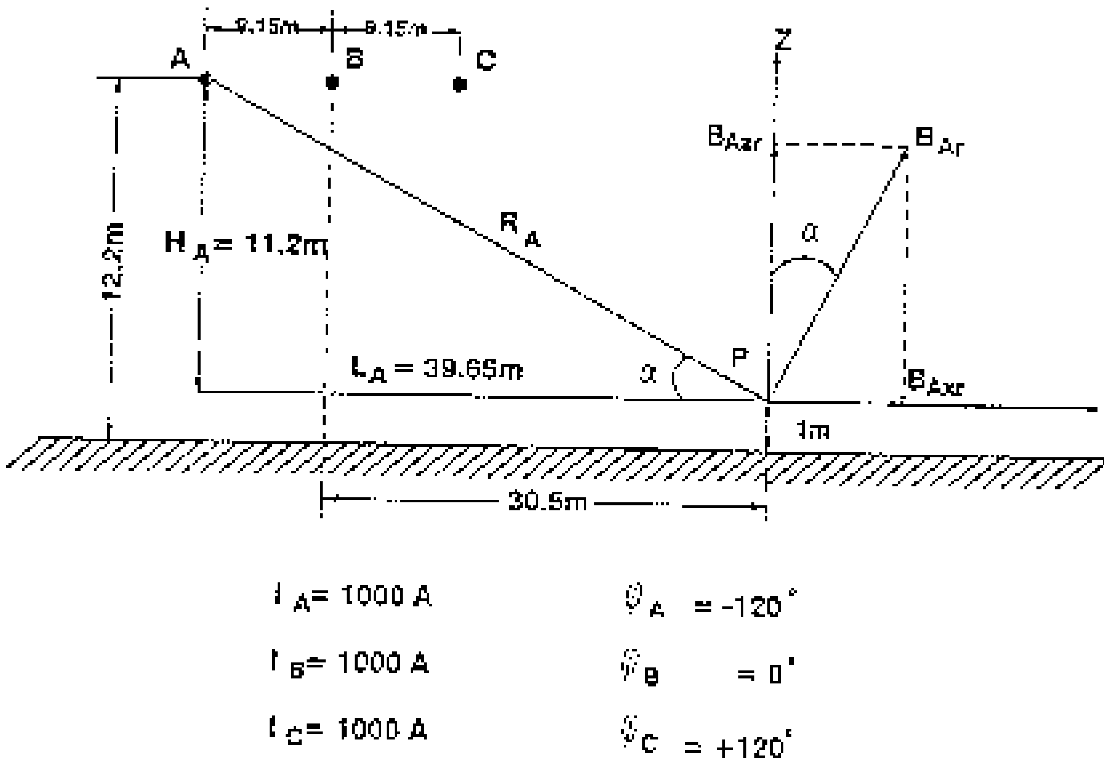


Figure 10
Example Data Needed to Calculate the Magnetic Field Near an Overhead Transmission Line

The same is done for the real parts of the vertical components and for the imaginary parts of the horizontal and vertical components.

A specific example is indicated in Table 2. For this example:

Horizontal component, real part	$B_{x_r} = -4.65 \cdot 10^{-7}T$
Vertical component, real part	$B_{z_r} = -2.31 \cdot 10^{-7}T$
Horizontal component, imaginary part	$B_{x_i} = 21.95 \cdot 10^{-7}T$
Vertical component, imaginary part	$B_{zi} = 23.17 \cdot 10^{-7}T$

A magnetic field meter with its probe oriented to measure the horizontal component will measure a magnetic field obtained by combining the horizontal component's real and imaginary parts as follows:

$$B_x = \sqrt{B_{x_r}^2 + B_{x_i}^2} = 22.44 \cdot 10^{-7}\text{T}$$

Table 2
Step-By-Step Calculation Of Magnetic Field At A Point Near A 3-Phase Overhead Transmission Line (see Figure 10)

	Current		Current		Geometric variables		
Phase	Magnitude	Phase	Real	Imaginary	H	L	R
	(ampere)	(degree)	(ampere)	(ampere)	(meter)	(meter)	(meter)
			$I_r = I \cos\varphi$	$I_i = I \sin\varphi$			$R = \sqrt{H^2 + L^2}$
A	$1_A = 1000$	$\varphi_A = -120$	$I_{Ar} = -500$	$I_{Ai} = -866$	$H_A = 11.2$	$L_A = 39.65$	$R_A = 41.20$
B	$I_B = 1000$	$\varphi_B = 0$	$I_{Br} = 1000$	$I_{Br} = 0$	$H_B = 11.2$	$L_B = 30.50$	$R_B = 32.49$
C	$I_C = 1000$	$\varphi_C = +120$	$I_{Cr} = -500$	$I_{Ci} = 866$	$H_C = 11.2$	$L_C = 21.35$	$R_C = 24.41$

Magnetic Field				
	Real		Imaginary	
Phase	Horizontal (tesla)	Vertical (tesla)	Horizontal (tesla)	Vertical (tesla)
	$B_{xr} = 2 \cdot 10^{-7}\, I_r\, H/R^2$	$B_{zr} = 2 \cdot 10^{-7}\, I_r\, L/R^2$	$B_{xi} = 2 \cdot 10^{-7}\, I_i\, H/R^2$	$B_{zi} = 2 \cdot 10^{-7}\, I_i\, L/R^2$
A	$B_{Axr} = -6.60 \cdot 10^{-7}$	$B_{Azr} = -23.37 \cdot 10^{-7}$	$B_{Axi} = -11.43 \cdot 10^{-7}$	$B_{Azi} = -40.46 \cdot 10^{-7}$
B	$B_{Bxr} = 21.22 \cdot 10^{-7}$	$B_{Bzr} = 57.79 \cdot 10^{-7}$	$B_{Bxi} = 0$	$B_{Bzi} = 0$
C	$B_{Cxr} = -19.27 \cdot 10^{-7}$	$B_{Czr} = -36.73 \cdot 10^{-7}$	$B_{Cxr} = 33.38 \cdot 10^{-7}$	$B_{Czr} = 63.63 \cdot 10^{-7}$
Totals:	$B_{xr} = B_{Axr} + B_{Bxr} + B_{Cxr}$	$B_{zr} = B_{Azr} + B_{Bzr} + B_{Czr}$	$B_{xi} = B_{Axi} + B_{Bxi} + B_{Cxi}$	$B_{zi} = B_{Azi} + B_{Bzi} + B_{Czi}$
Horizontal Component	$B_x = \sqrt{B_{xr}^2 + B_{xi}^2} = 22.44 \cdot 10^{-7}$			
Vertical Component	$B_z = \sqrt{B_{zr}^2 + B_{zi}^2} = 23.28 \cdot 10^{-7}$			
RMS Resultant	$B_{rms} = \sqrt{B_x^2 + B_z^2} = 32.33 \cdot 10^{-7}$			
Maximum Field	$Tan\beta_1 = 1.077$	$(\beta_1 = 47.13°)$	$B_{max} = 32.21.10^{-7}$	
Minimum Field	$Tan\beta_2 = -0.928$	$(\beta_2 = -42.86°)$	$B_{min} = 32.21.10^{-7}$	

Similarly, if the probe is oriented to measure the vertical component, it will measure:

$$B_z = \sqrt{B_{zr}^2 + B_{zi}^2} = 23.28 \cdot 10^{-7}\text{T}$$

Finally, the resultant field is:

$$B_{rms} = \sqrt{B_x^2 + B_z^2} = 32.33 \cdot 10^{-7}\text{T} = 32.33\text{mG}$$

Since the currents used to calculate the magnetic field are r.m.s. values, the resultant field also is an r.m.s. value.

The maximum field, B_{max}, which is the r.m.s. value of the field measured in the direction of the major axis of the field ellipse, is calculated as follows:

The angle, β, of the major axis of the ellipse with the horizontal is found (EPRI Transmission Line Reference Book, Second Edition, page 409) by solving the following quadratic equation:

$$\left(\tan^2 \beta\right)\left(B_{x_r} \cdot B_{z_r} + B_{x_i} \cdot B_{z_i}\right) + \left(\tan \beta\right)\left(B_{x_r}^2 + B_{z_r}^2 - B_{x_i}^2 - B_{z_i}^2\right)\left(B_{x_r} \cdot B_{z_r} + B_{x_i} \cdot B_{z_i}\right) = 0$$

This equation has two solutions, corresponding to the major and minor axes of the ellipse.

For our example, the two solutions are:

$\tan \beta_1 = 1.077$ ($\beta_1 = 47.13^\circ$)

$\tan \beta_2 = -0.928$ ($\beta_2 = -42.86^\circ$)

The magnetic field components measured along the major and minor axes of the field ellipse are given by:

$$B_{\max} \text{ (or } B_{\min}) = \sqrt{(B_{x_r} \cos\beta + B_{z_r} \sin\beta)^2 + (B_{x_i} \sin\beta + B_{z_i} \cos\beta)^2}$$

when β assumes the value of β_1 or β_2.

For our example:

$\beta_1 = 47.13^\circ$ gives $B_{max} := 32.21 \cdot 10^{-7}\text{T}$ (32.21 mG)

and

$\beta_2 = 42.86^\circ$ gives $B_{min} = 2.75 \cdot 10^{-7}$T (2.75 mG)

It is interesting to note that $\sqrt{B_{max}^2 + B_{min}^2} = 32.33\text{mG} = B_{rms}$

The degree of polarization is expressed by the axial ratio $B_{min}/B_{max} = 0.09$. The ellipse is very narrow, i.e., the field is almost linearly polarized.

Effect of Overhead Ground Wires

Calculations of magnetic field from overhead transmission lines require that the currents in all the wires be known, including the currents in overhead ground wires (or counterpoises) used for protection from lightning. If ground wire currents are not known, they may he calculated. Calculation methods for ground wire currents are not generally accurate. However, in most practical cases, their contribution to the magnetic field is small in comparison to that of the phase wires.

Magnetic Field Calculations in 3-D

The calculations provided by ENVIRO and by the BPA program are solutions of a two-dimension problem. These programs are not applicable if the line has turns, or if the effect of the line sag needs to be assessed, or if the wires are not parallel to each other such as in spans along which the line configuration changes (e.g. goes from vertical to horizontal while entering a substation), or if two lines cross each other.

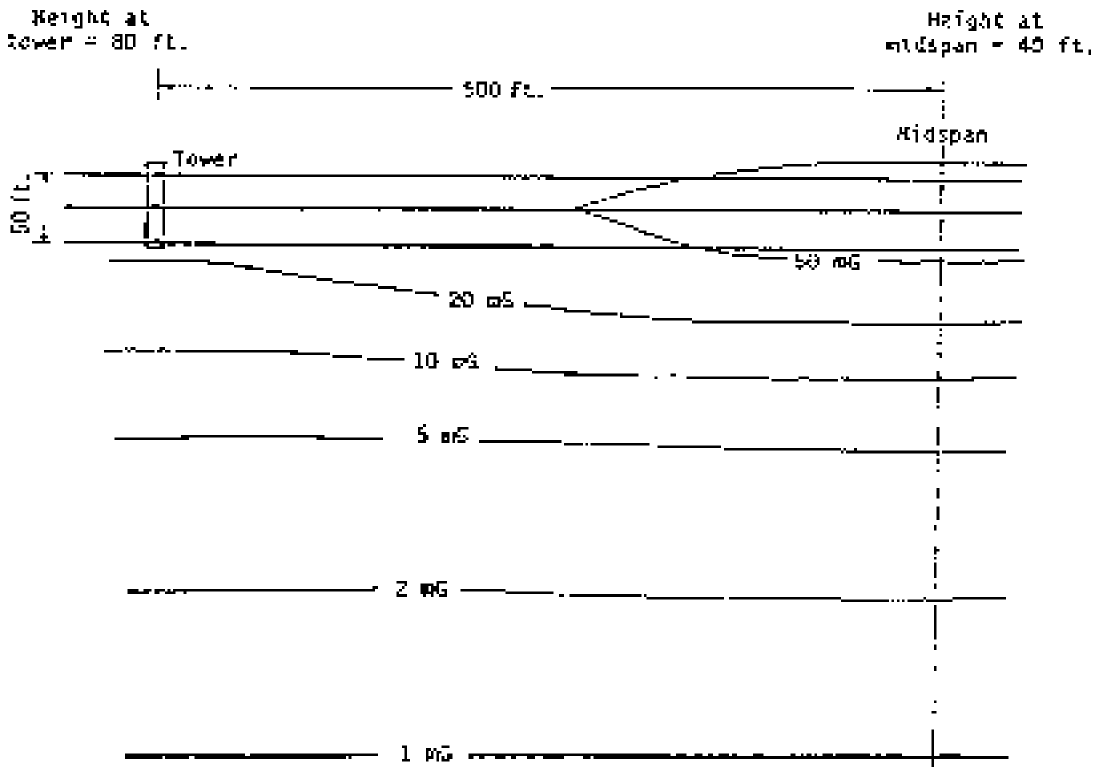


Figure 11
Contour Lines Calculated Using a 3-D Computer Program (EPRI's MAG3D) Which Accounts for the Conductor Sag. Calculations Made for a Line Current of 500 A

In these cases, computer programs that can solve magnetic fields in three dimensions must be used. One such program is MAG3D, which is a part of EPRI's TL Workstation™· MAG3D offers an exact solution. An approximate solution is offered by EXPOCALC, another EPRI program. Results from 3-D programs can be displayed as contour lines separating regions with different field magnitudes.

FIELD OUTSIDE THE RIGHT-OF-WAY (DISTANT FIELD)

Most human exposure to magnetic field occurs outside the right of way in the so called "distant field". Distant field is defined as the field at locations whose distance to the center of the power line conductors is equal to several (>3) times the average distance between the transmission line conductors.

As we have shown, the customary method of calculation of the magnetic field produced by a transmission line is to calculate the field caused by each phase separately and then add up the contributions of each phase. While this method is accurate, its use for the purpose of optimizing the line geometry requires a trial and error procedure with calculations repeated for each proposed geometry.

The "distant field" of transmission lines can be analyzed much more efficiently by reducing the set of line currents into basic line current elements.

Three basic line current elements are the monopole, dipole, and quadrupole. The study of the structure of the magnetic field produced by these line current elements yields quite interesting results, as shown in Figure 12. The field varies in inverse proportion to the distance, the square of the distance, and the cube of the distance, for monopole, dipole, and quadrupole respectively. Any line current set can be reduced into these (or higher order) elements. This method of analysis is profitable because:

simple equations can be derived to express the distant field as a function of line parameters

certain techniques for distant field reduction become apparent

Using the techniques of reduction of line current sets into monopoles, dipoles, and quadrupoles, the following simple equations for the distant field can be derived. In all cases, the equations give the r.m.s. value of the field. If the field is not linearly polarized, the r.m.s. value is greater than the maximum field component (major axis of the field ellipse).

3-Phase, Flat Configuration, Balanced and Symmetric Currents

$$B = 2\sqrt{3}\, PI / R^2$$

where:

B is the r.m.s. value of the magnetic field (mG)
P is the phase spacing (m)
I is the phase current (A)
R is the distance from center phase (m)
The field is linearly polarized.

For example, let us calculate the field of the 3-phase line for which the exact calculations were made step-by-step in Table 2.

The distance to the center of the line (phase B) is:

$$R = \sqrt{11.2^2 + 30.5^2} = 32.49 \text{ m}$$

$$B = 2 \cdot \sqrt{3} \cdot 9.15 \cdot \frac{1000}{32.49^2} = 30.03 \text{ mG}$$

This value is about 7% lower than the exact value. The difference between the distant field equation and the exact solution becomes smaller as the distance from the line increases. For example, at 150 ft (45.75 m), this difference is only about 1%.

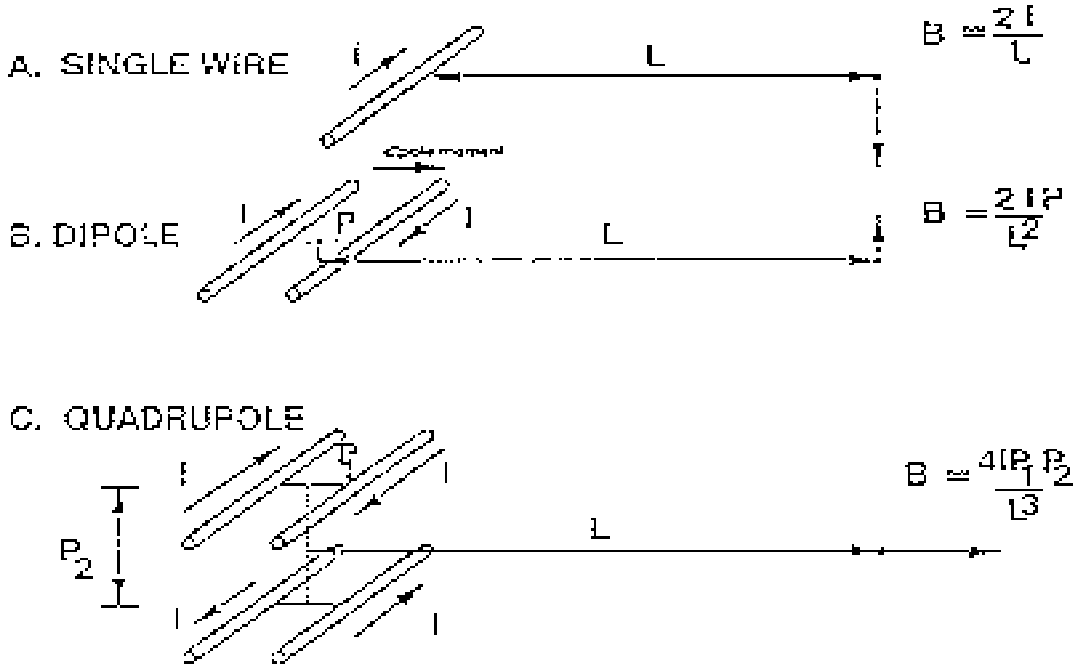


Figure 12
Equations for Magnetic Fields of Simple Line Geometries

<u>3-Phase, Vertical Configuration</u>

$$B = 2\sqrt{3}\,\frac{PI}{R^2}$$

The field is linearly polarized.

<u>3-Phase, Equilateral Delta</u>

$$B = \sqrt{6}\,\frac{PI}{R^2}$$

The field is circularly polarized. The field component is the same in all directions and is equal to the r.m.s. value divided by $\sqrt{2}$.

This equation can also be written in terms of S, the radius of the configuration circle, which is related to the phase spacing, $P_{3\phi}$, of the 3-phase equilateral delta, as: $S/P_{3\phi} = 1/\sqrt{3}$

The equation is:

$$B = 3\sqrt{2}\frac{SI}{R^2}$$

where: B in the r.m.s. value of the magnetic field (mG).
S is the radius of the configuration circle (m).
$P_{3\phi}$ is the phase spacing of the 3-phase, equilateral configuration.
I is the current in each phase of the 3-phase line (A).
R is the distance from the center of the configuration circle (m).

3-Phase, Non-Equilateral Delta

$$B = \sqrt{3P_h^2 + 4P_v^2}\,\frac{I}{R^2}$$

where: P_h is the distance between the two outer phases (m).
P_v is the vertical offset of the center phase (m).
The field is elliptically polarized.

3-Phase, Any Geometry

$$B = \sqrt{2}\cdot\sqrt{P_{ab}^2 + P_{ac}^2 + P_{bc}^2}\,\frac{I}{R^2}$$

where: P_{ab} P_{ac}, and P_{bc} are the distances (m) between phases A and B, A and C, and B and C, respectively.

6-Phase, Circular Configuration

$$B = 6\sqrt{2}\frac{SI}{R^2}$$

where: I is the current in each phase of the 6-phase line (A).

The field is circularly polarized. The field component is the same in all directions and is $\sqrt{2}$ times smaller than the r.m.s. value of the field.

6-Phase, Vertical Configuration

$$B = 4\sqrt{P_h^2 + 3P_v^2}\,\frac{I}{R^2}$$

where: P_h is the horizontal distance between two sets of three vertically stacked phases (m).

P_v is the vertical phase spacing (m).

I is the current in each phase of the 6-phase line (A).

The field is elliptically polarized.

12-Phase, Circular Configuration

$$B = 12\sqrt{2}\,\frac{SI}{R^2}$$

where: S is the radius of the configuration circle (m).

I is the current in each phase of the 12-phase line (A).

The field is circularly polarized.

Comparison between the equations for 3-phase, equilateral delta, and 6-phase, circular configuration, shows that the 6-phase line with the same voltage-to-ground and carrying the same power (current per phase equal to one half) of a 3-phase line will produce the same field as a 3-phase line. This assumes that the radius, S, of the configuration circle is the same for both lines. The $S/P_{3\phi}$, ratio is also the same as the phase-to-phase voltage ratio for the two configurations. Therefore, if phase-to-phase distances are kept proportional to phase-to-phase voltages, the magnetic field produced by a 6-phase line is the same as that produced by a 3-phase line. This statement is true also for higher phase order (e.g. 12-phase) lines. For the 12-phase line, the ratio of the distances and of the phase-to-phase voltages is $S/P_{12\phi} = (\sqrt{6}+\sqrt{2})/2 = (\sqrt{3}+1)/\sqrt{2}$, where $P_{12\phi}$ is the phase spacing of the 12-phase configuration.

Double Circuit Lines

The lowest magnetic fields will be obtained when the two circuits are in the "low reactance" configuration (ABC, CBA phasing), and when the two circuits carry equal currents. In this case, the configuration is equivalent to a quadrupole (see Figure 13). When the currents of the two circuits are not equal, the distant field has a dipolar component that decays with $1/R^2$ and a quadrupolar component that decays with $1/R^3$. For example, consider a double circuit line with vertical configuration (Ph is the horizontal separation between the two circuits, Pv is the vertical phase spacing) in the low-reactance (ABC, CBA) arrangement. Further, assume that the currents (I_1, I_2 with $I_1 > I_2$) in the two circuits are balanced and symmetric and have the same phase angles. The dipolar and quadrupolar components, B_d and B_q, are:

$$B_d = 2\sqrt{3}(I_1 - I_2)\frac{P_v}{R^2}$$

$$B_q = 4I_2P_v.\frac{\sqrt{P_v^2 + 3P_h^2}}{R^3}$$

where: I_1, 1_2 are the currents in each phase of the respective lines, 1 and 2.

If $I_1 = I_2$, the dipolar component is zero. There is only a quadrupolar component and the field will vary inversely with R^3.

If $I_1 \neq I_2$, the dipolar component predominates at distances larger than a distance, R_d, given by:

$$R_d = \frac{2}{\sqrt{3}}.\frac{I_2}{(I_1 - I_2)}.\frac{\sqrt{P_v^2 + 3P_h^2}}{R^3}$$

For instance, if I_2=0.5I_1 and P_v=P_h, then R_d=2.3P_v. For all practical distances, the field will be equal to its dipolar component.

In all cases, the distant field of a double circuit low-reactance line will be less than that produced by the circuit with the highest current, if it were alone. This is because the second circuit acts to partially cancel the magnetic field of the first circuit.

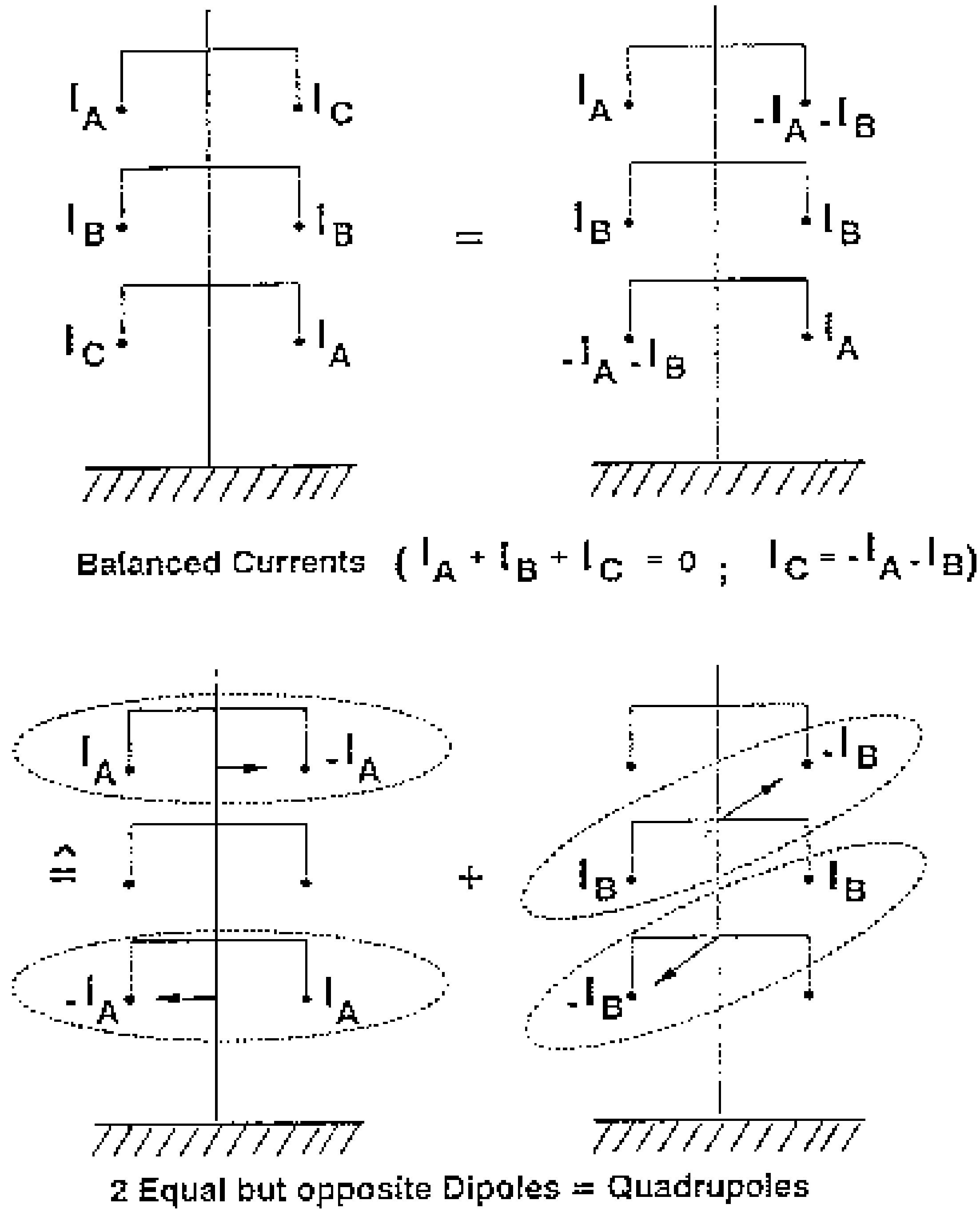


Figure 13
Reduction of a Double Circuit Line into Two Quadrupoles

WHICH FIELD CHARACTERISTICS MAY BE IMPORTANT

Most studies of human exposure to power system magnetic fields use the average magnetic field over a measurement period, the so called "time weighted average" (TWA) of the 60 Hz field. If the field is measured from T1 to T2 over a period of time T = T2 - T1,

$$TWA = \frac{1}{t}\int_{t_1}^{t_2} Bdt$$

where B is the 60 Hz r.m.s. field. To date, however, a biologically appropriate exposure metric for magnetic fields has not been identified.

Two recent studies of childhood cancer (Savitz, London) reported similar results: a moderate and statistically significant association when "wiring codes" are used as the exposure index, and a lower and not significant association with spot 60 Hz field measurements (Savitz, London) and with measured TWA magnetic fields (London). Among the possible explanations for these findings is the assumption that wire codes are a surrogate for magnetic field characteristics other than TWA and that these characteristics cannot be satisfactorily predicted on the basis of TWA measurements.

A recently completed Swedish study (4), however, suggests that the calculated annual time weighted average power frequency (50 Hz in Sweden) magnetic field is correlated to childhood leukemia.

Even if exposure to 60 Hz fields can produce health effects, there is no agreement on the nature of the "effect function" which relates exposure to health effect. An effect function relates a specific pattern of field exposure over time to a resulting health response. Studies performed at the cellular or biological function level suggest a variety of possible effect functions, but these are all hypotheses that require additional studies.

Examples of effect functions other than the time weighted average of the magnetic field strength are:

- Cumulative field strength within a range of fields (window)
- Cumulative time during which the field is within a range (window)
- Frequency of excursions above a field threshold
- Frequency of field changes
- Number of "intermittents"
- Average field strength during certain periods of time (e.g. night time average field)

Also, field parameters other than the 60 Hz r.m.s. value may be important.

Cumulative Field Strength Within a Window

The cumulative field strength is the metric commonly referred to as cumulative exposure or "dose", i.e., the product of strength and time. In many physical systems, effects are related to cumulative exposure above a threshold level; in some instances, a window effect has been reported. The cumulative exposure is represented in Figure 14, and is expressed by the indicator I(t), where:

$I(t) = 0$ when $B_{TL} > B(t)$ or $B(t) > B_{TU,}$

$I(t) = B(t)$ when $B_{TL} \leq B(t) \leq B_{TU}$

and

$$B_{cum} = \int_{t_1}^{t_2} I(t)dt$$

where

B_{cum} = Cumulative Field Exposure

B_{TL} = Lower Threshold level of field strength, below which no effects occur

B_{TU} = Upper Threshold level of field strength, above which no effects occur

I(t) = Indicator related to B(t)

Note that setting the upper threshold to infinity opens the window such that only the lower threshold is operative. If, in addition, the lower threshold is zero, the cumulative field exposure is equal to TWA. $(T_2 - T_1)$.

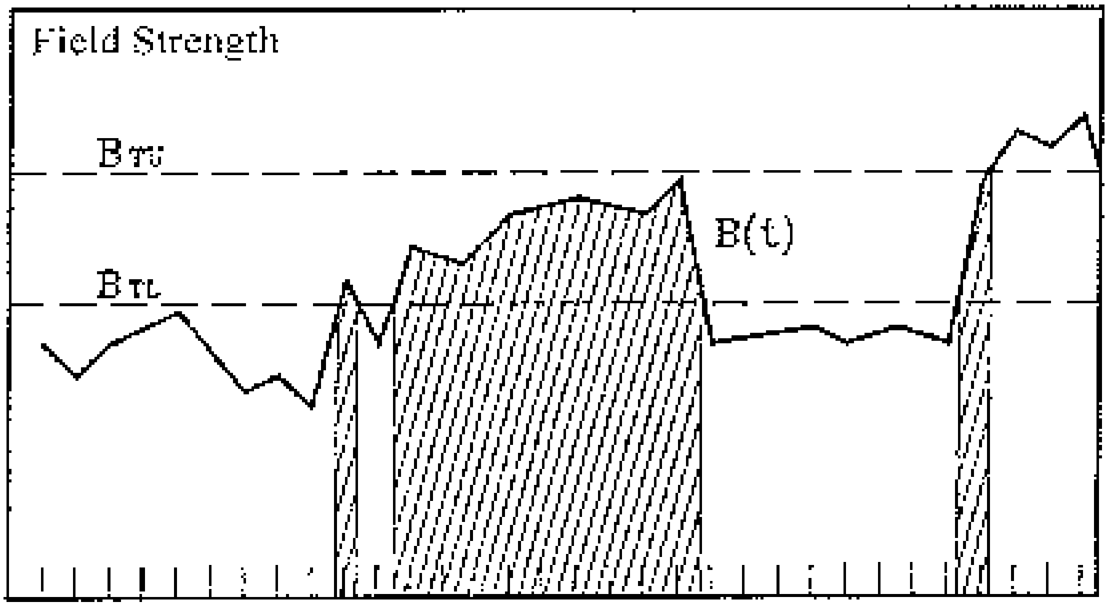


Figure 14
Cumulative Field Exposure Within a Window

Cumulative Time Field is in a Window

This effect function relates to the total time that the field strength is between lower and upper threshold limits. As a special case, setting the upper threshold to infinity yields the total time that the field strength exceeds the lower threshold. This effect function is shown in Figure 15, and is represented by:

$I_i = 0$ if $B_{TL} > B_i$ or $B_i > B_{TU}$

Otherwise,

$I_i = \Delta T$ if $B_{TL} \leq B_i \leq B_{TU}$

and

$$T_{cumj} = \sum_i I_i$$

where: T_{cumj} = Cumulative time field has been within the window over j intervals

ΔT = Time increment between field strength samples

B_i = i th sample of B(t)

I_i = Indicator related to Bi

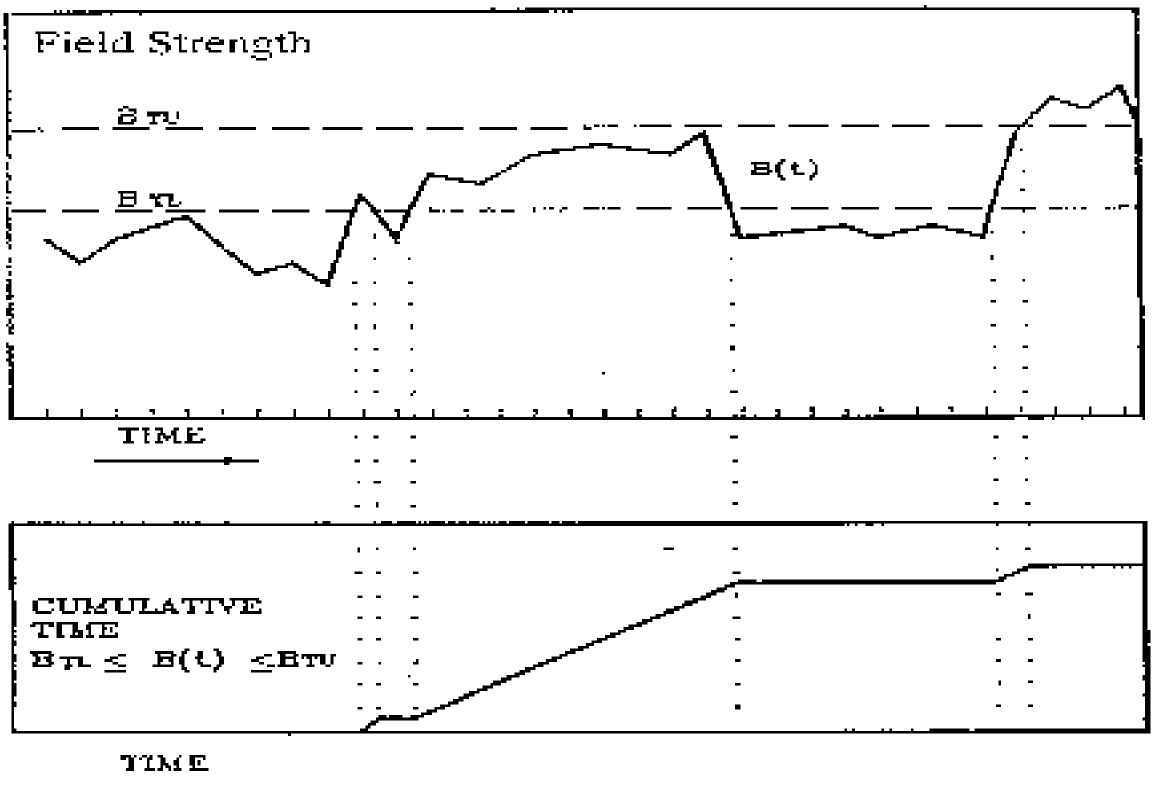


Figure 15
Cumulative Time Within Field Window

Frequency of Excursions Above a Field Threshold

This effect function is based on the number of instances when the field strength is sampled and is above a lower threshold level. The effects function corresponding to excursion frequency is depicted in Figure 16 and is represented by:

$I_i = 0$ if $B_i < B_T$

Otherwise,

Ii = l if $B_i > B_T$

and

$$N_j = \sum_i I_i$$

where:

N_j = Number of times i samples of B(t) have equaled or exceeded the threshold B_T in interval j

B_i = i th sample of B(t)

I_i = Indicator related to Bi

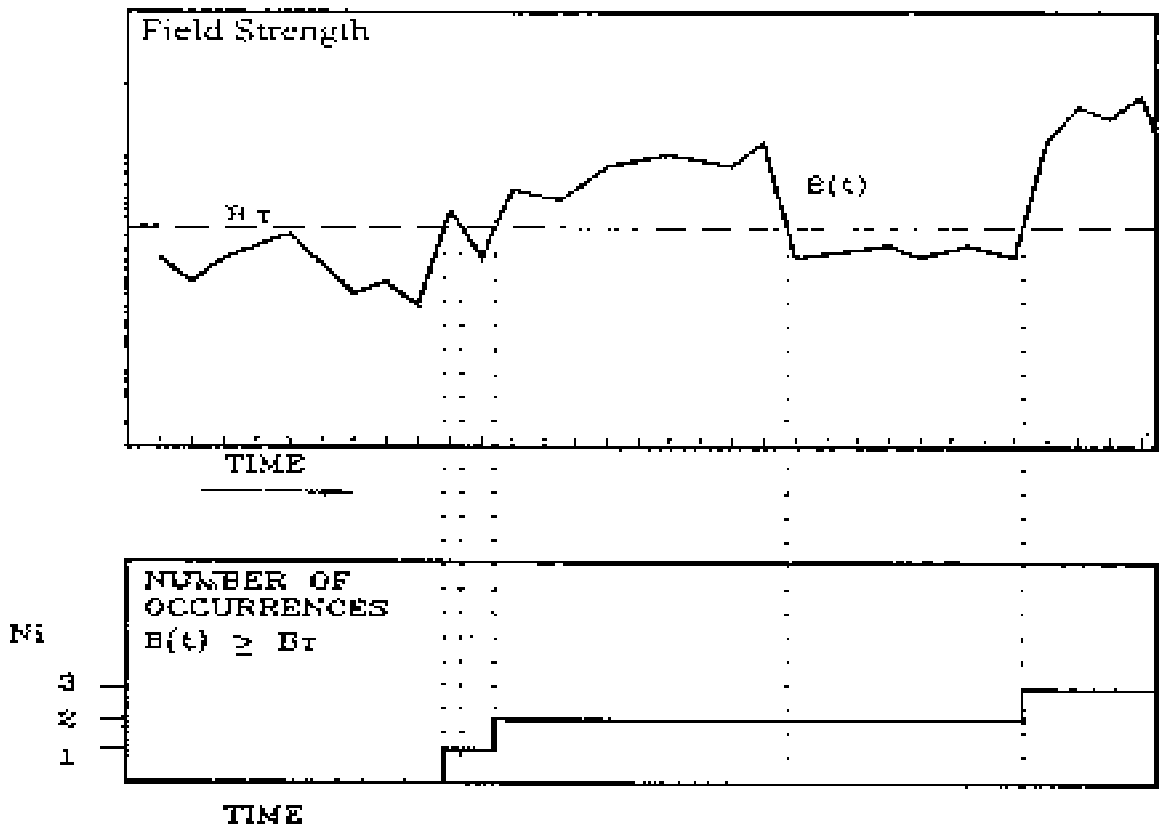


Figure 16
Frequency of Excursions Above Threshold

Number of Intermittents

A "magnetic field intermittent" is defined as a magnetic field event during which the r.m.s. value of the magnetic field has a significantly different value than before or after the event. An example of intermittent is shown in Figure 17. An intermittent is characterized by its duration and its average value. The rate of intermittency is the number of intermittents in an hour or in a day.

Average Field Strength During Certain Periods of Time-(e.g. Nighttime Average Field)

This effect function relates to results which depend on exposure during certain periods of time. For instance, the nighttime average field strength is:

$$B_{nt} = \frac{1}{T_2 - T_1} \int_{t_1}^{t_2} B(t)dt$$

where T_1 and T_2 are the times at the beginning and at the end of the nighttime period.

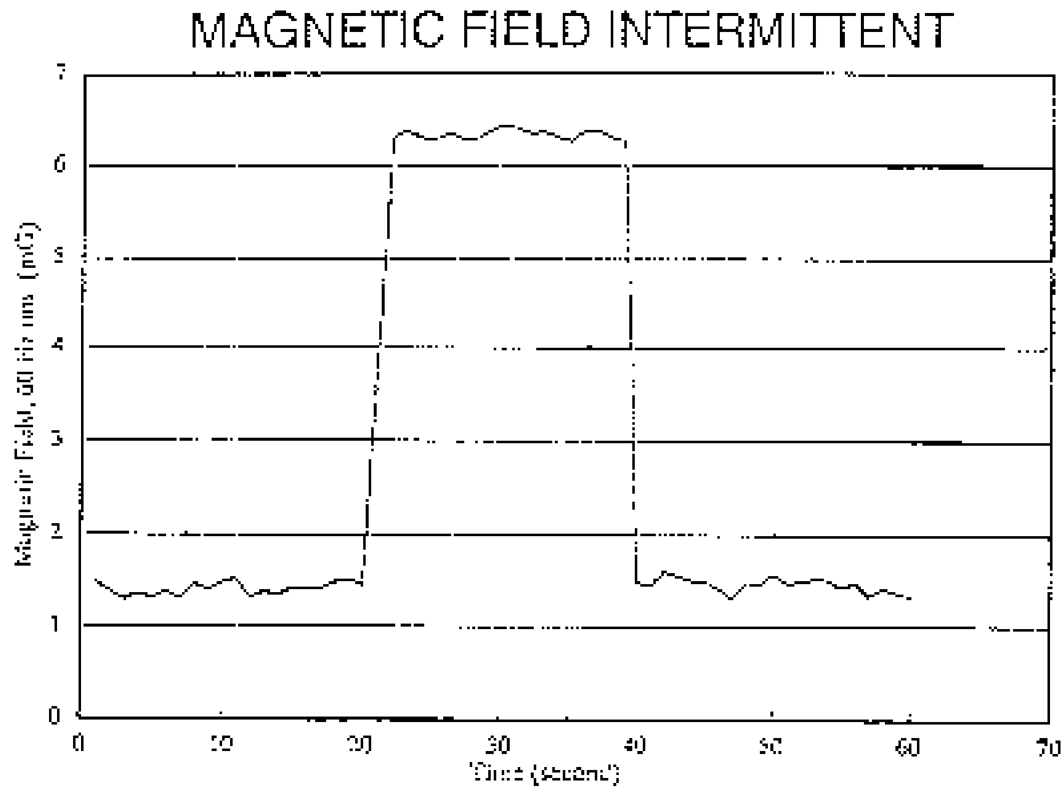


Figure 17
Magnetic Field Intermittent

Parameters Other Than 60 Hz r.m.s. Value

Parameters other than the 60 Hz r.m.s. field have been the subject of speculations. They include:

- Horizontal component of the magnetic field

- Harmonics of the 60 Hz magnetic field (previously defined)
- Magnetic field transients
- DC magnetic field in certain combinations with AC fields
- Cyclotron (and other resonance) hypotheses
- Degree of polarization (previously defined)

Magnetic Field Transients

A magnetic field transient may be defined as the "magnetic field during a period in which the field has rapid changes in values while passing from one steady state condition to another". The field during the transient changes fast enough that the derivative of the magnetic field with respect to time (dB/dt) reaches a peak value significantly greater than the peak values of dB/dt in the steady state conditions before and after the transient. Implied in this definition is the assumption that the interest in transients is due to the potential biological effect of dB/dt, and therefore transient events with dB/dt that are not significantly greater than the steady state value of dB/dt are of little interest.

A transient is characterized by the function field (B) [or field derivative (dB/dt)] versus time. From this function, a number of parameters can be derived such as: peak dB/dt, transient duration, oscillation frequency, and decay time.

For instance, the transient shown in Figure 18 has a peak dB/dt of 15 gauss/second (absolute value), a duration of about 4 millisecond, an oscillation frequency of about 350 Hz, and a decay time constant of about 1.5 millisecond. The absolute value of the peak dB/dt of the transient (15 G/s) is significantly larger than the absolute values of the peak dB/dt during the steady state periods immediately preceding and following the transient (0.38 G/s and 0.75 G/s, respectively).

Instruments that measure magnetic field transients do so by measuring the component of the field (or of the field derivative) along specified axes. A complete characterization is possible if the field components are measured along three orthogonal axes.

Certain transients events are not transients according to the definition given above, but should rather be classified as "intermittents". The magnetic field event described by Figure 17, for instance, is not classified as a transient. In fact, the figure plots the 60 Hz r.m.s. value and not the instantaneous value of the magnetic field. We do not know whether or not the derivative of the instantaneous value of the magnetic field reached a significant peak value. The insertion of an electrical load may cause a large variation in 60 Hz rms. magnetic field, but not necessarily a dB/dt value greater than those preceding or following the event.

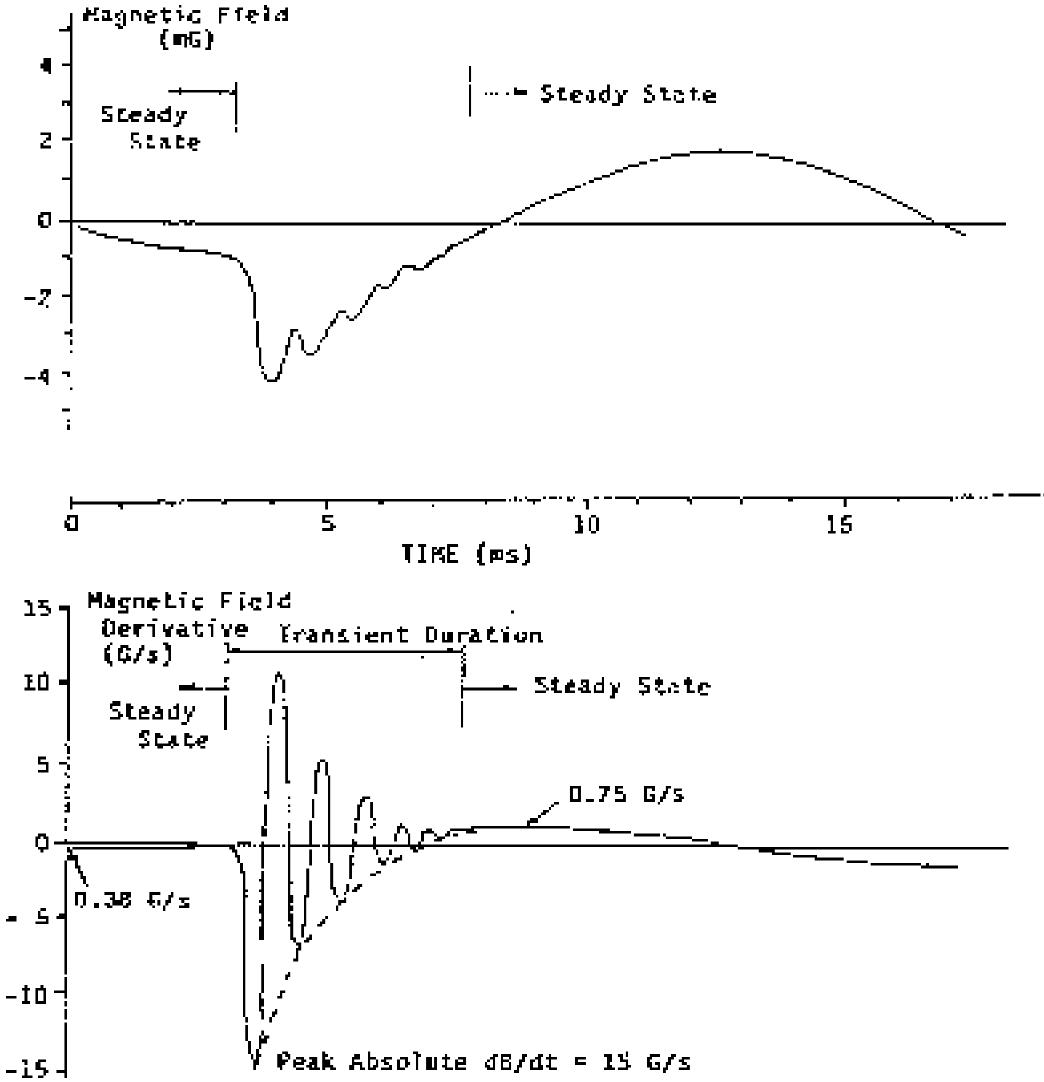


Figure 18
Magnetic Field Transient

Example Comparison of Magnetic Field Characteristics Between Overhead Transmission Line and Grounding System

The characteristics of the magnetic field produced by an overhead transmission line inside a residence near the line are compared to those produced in another residence by the currents in the grounding system of that residence. The results of this comparison, shown in Table 3, are based on the time functions shown in Figure 6. Although this is just an example, it shows that transmission line fields can be quite different from fields of other sources even when both have the same time weighted average. The threshold levels were selected only as an illustration and are not based on actual data.

Table 3

Example Comparison Of Characteristics Of Residential Magnetic Field Produced By An Overhead Transmission Line And By The Grounding System During a 24-hour period)

	Overhead Transmission Line	Grounding System
Time Weighted Average (24-hour average at one point inside the residence)	3.19 mG	3.19 mG
Cumulative strength above a threshold (e.g. >3mG)	58.3 mG.h	51.2 mG.h
Cumulative strength within a window (e.g. 2mG<B<4mG)	69.2 mG.h	62.4 mG.h
Cumulative time field is in a window (e.g. 2mG<Br<4mG)	126.3 min	121.6 rain
Frequency of excursions above a field threshold (e.g. 2.5mG)	5	124
Number of Intermittents (difference of lmG between upper and lower threshold. duration greater than I min)	0	90
Nighttime Field Average. (11 p.m.-6 a.m.)	2.21 mG	2.94 mG
Number of Transients	unknown	unknown
Horizontal Component Average	0.34 mG	2.32 mG

EXPOSURE TO TRANSMISSION LINE FIELDS

When the interest in power system magnetic field is focused on human exposure, the magnetic field must be characterized over the area and time period which accounts for peoples' activity patterns. Very little is known about public exposure to transmission line magnetic fields. Longterm magnetic field exposure from transmission lines is difficult to characterize because magnetic fields from transmission lines are a function of line currents (balanced and unbalanced), which vary as a function of time of day, week, or year and as a function of weather and other external influences.

The magnetic field at any location is seldom, if ever, as large as calculated. The calculation is typically a worst case scenario that rarely occurs in practice because it is based on one of the following ratings of the line:

- Peak load
- Emergency load
- Design load
- Winter normal continuous capacity of the circuit
- Winter normal continuous capacity of the conductors
- Winter short-time emergency rating of the conductors

These ratings are variously defined by different utilities and power pools. Utilities typically operate their transmission lines well below these levels.

The relation between actual magnetic field and calculated magnetic field at one of the above line rating values is a function of the type of line. For instance, New York State utilities estimate that the yearly mean magnetic field at the edge of the right of way of their EHV transmission lines is only about 10% of the magnetic field calculated in the conditions of winter short-time emergency conductor rating.

Another important factor for the assessment of public exposure to transmission line fields is the distance from the line. The locations where public exposure is of greatest concern are outside the right of way, at distances where the magnetic field may be affected not only by the balanced currents of the line, but also by the zero sequence current, especially the fraction of the zero sequence current that flows into the earth (net current). There is little information on the net current, its value, phase angle, and temporal variations.

For instance, the magnetic field of a transmission line with 20 ft phase spacing carrying a balanced three phase current of 500 A is 1.2 mG at 300 fl. At this distance, a net current of 20 A produces a field of 0.5 mG which combines (it may add or subtract) with the field from the balanced current.

The relative effect of the net current is much greater for those transmission lines whose design is conducive to low magnetic field. For instance, a vertical double circuit line (20 ft phase spacing, 40 ft separation between circuits), with low reactance configuration, carrying 500 A on each circuit, has a field caused by balanced currents which may be as low as 0.3 mG at 300 fl. This value is lower than the 0.5 mG field which would be produced by a 20 A net current.

These considerations are particularly important whenever design options intended to reduce transmission line magnetic field are considered. If the net current values are significant, a design option that produces a large field reduction near the line (e.g. at the edge of the right of way) may not appreciably reduce public exposure to magnetic field, which takes place at distances further from the transmission line.

COMPARISON OF EXPOSURE FROM DIFFERENT SOURCES

Although many measurements are available to characterize the magnetic field from different sources, few comparisons of public exposure to magnetic fields are available. Only a small segment of the population lives close to transmission lines, and even for this segment, a significant portion of the magnetic field exposure may originate from other sources, such as currents in electrical appliances, the residence's grounding system, house wiring, and power distribution lines. In addition, significant magnetic fields may exist in non-residential environments, in which people may spend a significant portion of their time. In other words, transmission line magnetic field exposure must be considered in the context of a general "background" exposure, from which it may not be distinguishable. This view of transmission line magnetic field exposure is quite different from the traditional considerations of magnetic fields in the right of way under exceptional line loading conditions.

Although transmission lines are considered by many to be one of the most significant sources of magnetic fields, public exposure to transmission line magnetic fields may be insignificant as compared to that of other sources.

So far, we have considered the time weighted average exposure to 60 Hz fields. If future research suggests that other aspects of the magnetic fields are more relevant, exposure from transmission lines may increase or decrease in importance (depending on which parameter is considered):

<u>Parameter/effect on transmission lines' importance</u>

- Cumulative field strength within a window. Will depend on the window.
- Cumulative time field is in a window. Will depend on the window.
- Frequency of excursion above a field threshold. Because of their lower variability in pace and time, transmission lines will have a low ranking.
- Frequency of field changes. Same as above.
- Number of intermittents. Transmission lines will have a very low ranking.
- Horizontal component of the magnetic field. Transmission line ranking could be high or low depending on line design.
- Harmonics of the 60 Hz magnetic field. Transmission lines will have a very low ranking.
- Magnetic field transients. Transmission lines are likely to have a low ranking. However, not enough is known on the comparative value of transmission lines' and other sources' transients.
- DC magnetic fields in certain combinations with AC fields. Resonance phenomena postulated as a basis of biological effects depend on the value of the DC field and on its direction relative to that of AC fields. Therefore, transmission line exposure to this effect will depend on the local characteristics of the earth DC field (and its

modifications by ferromagnetic structures), and on the geometry and orientation of a transmission line.

- Degree of polarization. Whether transmission line field is polarized or not depends on the transmission line geometry. However, when transmission line field is in the presence of a field from another source, polarization will occur if the other source's field does not have the same direction and the same phase angle, a condition which is likely to occur often.

BETTER MAGNETIC FIELD CHARACTERIZATION NEEDED FOR TRANSMISSION LINES

Current knowledge is inadequate for a satisfactory assessment of transmission line magnetic fields vis-à-vis their possible impact on human health. A better characterization is needed for a variety of reasons:

- Current methods based on magnetic field calculations at the edge of the right of way and with the line at its maximum ratings greatly overstate peoples’ exposure. Exposure assessment based on actual line currents and actual distances of residences to the line would be more accurate.
- There is not enough information on the values of the net current and of its contribution to magnetic field exposure. Until such information is collected, peoples' exposure to transmission line magnetic field and the effectiveness of methods of transmission line magnetic field reduction cannot be properly assessed.
- The 60 H_z magnetic field average may not be the relevant parameter to be used in assessing the possible impact of magnetic fields on human health. Therefore, it is necessary to characterize all parameters of transmission line magnetic fields and compare them with those of other sources.

MAGNETIC FIELD MANAGEMENT

For each magnetic field source within the power system, there may be a number of design options to reduce magnetic field exposure without altering the function for which the system was intended. A general classification of the different approaches to magnetic field exposure reduction is the following:

1. Modification of activity patterns.

This approach consists of finding ways to minimize the presence of people at locations or at times of high magnetic fields. It may include:

- modification of work rules based on limiting magnetic field exposure, defined according to some specified metric,
- access limitation to areas in which magnetic fields are greater than some specified value,

- installation of facilities and equipment to minimize magnetic fields in areas frequently occupied by people.

2. Design of electrical facilities and equipment for lower magnetic fields.

This approach consists of modifying circuit, currents, or conductor arrangement, or characteristics of magnetic materials of facilities and equipment. This approach covers a large number of potential engineering options, some of which are discussed here.

3. Shielding

Magnetic field exposure may be reduced if the areas occupied by people are shielded from the magnetic field source. Conceptually, shielding methods can be divided into:

- Shielding caused by induced currents
- Shielding obtained by modification of magnetic flux patterns using high permeability materials
- Active shielding obtained by adding a magnetic field that tends to reduce the magnetic field present without shielding

The application of magnetic field exposure techniques to existing facilities and equipment is much more difficult than for new constructions. Existing facilities and equipment in general have severe constraints which limit the choice of suitable magnetic field reduction options and offer a new set of engineering challenges.

DESIGN OPTIONS FOR OVERHEAD TRANSMISSION LINES

Different options to minimize magnetic field have been conceptually developed, but for most of them, effectiveness, reliability, cost, and practicality have not yet been evaluated.

Effect of Line Configuration Line Compaction

Inspection of equations for the field outside the right of way show that:

The equilateral triangle (delta) configuration gives lower fields than the flat or other configurations for the same phase spacing. The r.m.s. value of the distant field of this configuration is $1/\sqrt{2}$ of that of a flat configuration. It should be noted that the field of an equilateral delta line is circularly polarized (the field vector describes a circle) while that of a flat configuration is linearly polarized. The biological significance of polarization, if any, is not known.

If the comparison is made on the basis of the maximum field component, the equilateral delta produces a field which is one half of that produced by a flat configuration.

The value of the field is inversely proportional to the square of the distance for all configurations. This is true only if the line current does not have a zero sequence component. The distant field caused by the zero sequence component is equal to $6I_o/R$ In the case of a flat configuration, this field becomes equal to that produced by the positive sequence I_p at a distance, R_o, from the center phase:

$$R_o = \frac{P}{\sqrt{3}} \cdot \frac{I_p}{I_o}$$

For instance, if $I_o = 0.03\ I_p$ and P = 25 ft, R_o = 480 ft

The value of the field is proportional to the phase spacing. Line compaction, therefore, is a method for achieving magnetic field reduction.

There are obvious limits to line compaction, dictated by insulation and corona noise requirements. From the lowest transmission voltages, up to 230 kV, insulation requirements are likely to be the limiting factor. At these voltages, significant degrees of compaction over traditional designs may be achieved at relatively low cost. At transmission voltages of 345 kV and above, corona noise is the major obstacle to phase compaction. Research on conductor designs to reduce corona noise is necessary to achieve a large degree of compaction.

Split-Phase Lines

To reduce the distant field, it is advantageous to reduce or eliminate the lower order components (monopolar or dipolar) which have a slower decay with distance.

The monopolar component is reduced to zero when the sum of all the currents ("net current") is zero. For a three-phase transmission line, this occurs when the zero sequence current is zero, or, if the line has ground wires, when the zero sequence current is carried exclusively by the ground wires.

The reduction of the dipolar component requires a system with more than three wires. It is well known, for instance, that a double circuit line of the low-reactance type carrying equal current in the two circuits produces a much lower distant field than a single circuit three-phase line. In fact, such a double circuit line can be shown to correspond to a quadrupole. The field decays in inverse proportion to the third power of the distance from the center of the line conductors. This concept can be extended to the so called split-phase lines for which the field is quadrupolar and varies in inverse proportion to the third power of the distance from the center of the line.

A split-phase line is still a 3-phase line. However, one or more of the phases is split into two or more conductors, (see Figure 19). The magnetic field lateral profiles of several split-phase arrangements are compared to that of a traditional flat design in Figure 20, which corresponds to a 230 kV line carrying 240 MW.

The field produced by the split-phase designs is considerably lower than that produced by the traditional design even at the center of the line and becomes increasingly lower as the distance from the line increases.

Split-phase lines result also in reduced electric field although the reduction is not as much as that of the magnetic field. An additional potential benefit is the significant reduction of the line surge impedance.

Split-phase designs may produce significantly higher levels of audible and radio noise than traditional lines. For line voltages of 115-138 kV, splitting the phases while keeping the total conductor cross-sectional area constant still results in acceptable noise levels. In fact, the design of the conductors for these lines is generally not limited by radio and audible noise design considerations. At 230 kV, phase splitting while maintaining the same total conductor cross-sectional area may result in designs that are marginal from the point of view of radio and audible noise.

Additional conductor cross-sectional area, however, may be needed for split-phase lines at 345 kV and even more at 500 kV. Each split-phase of a 500 line may require two bundles of two or three conductors each, of the same diameter as that of a traditional three-phase 500 kV line. Thus, the required total cross-sectional area is practically twice that of a traditional line. Therefore, the cost of this option will be substantially higher than that of a traditional line. Since the limitation in this case is due to corona, research on conductor designs to reduce corona is needed before making this concept practical for the highest voltage lines.

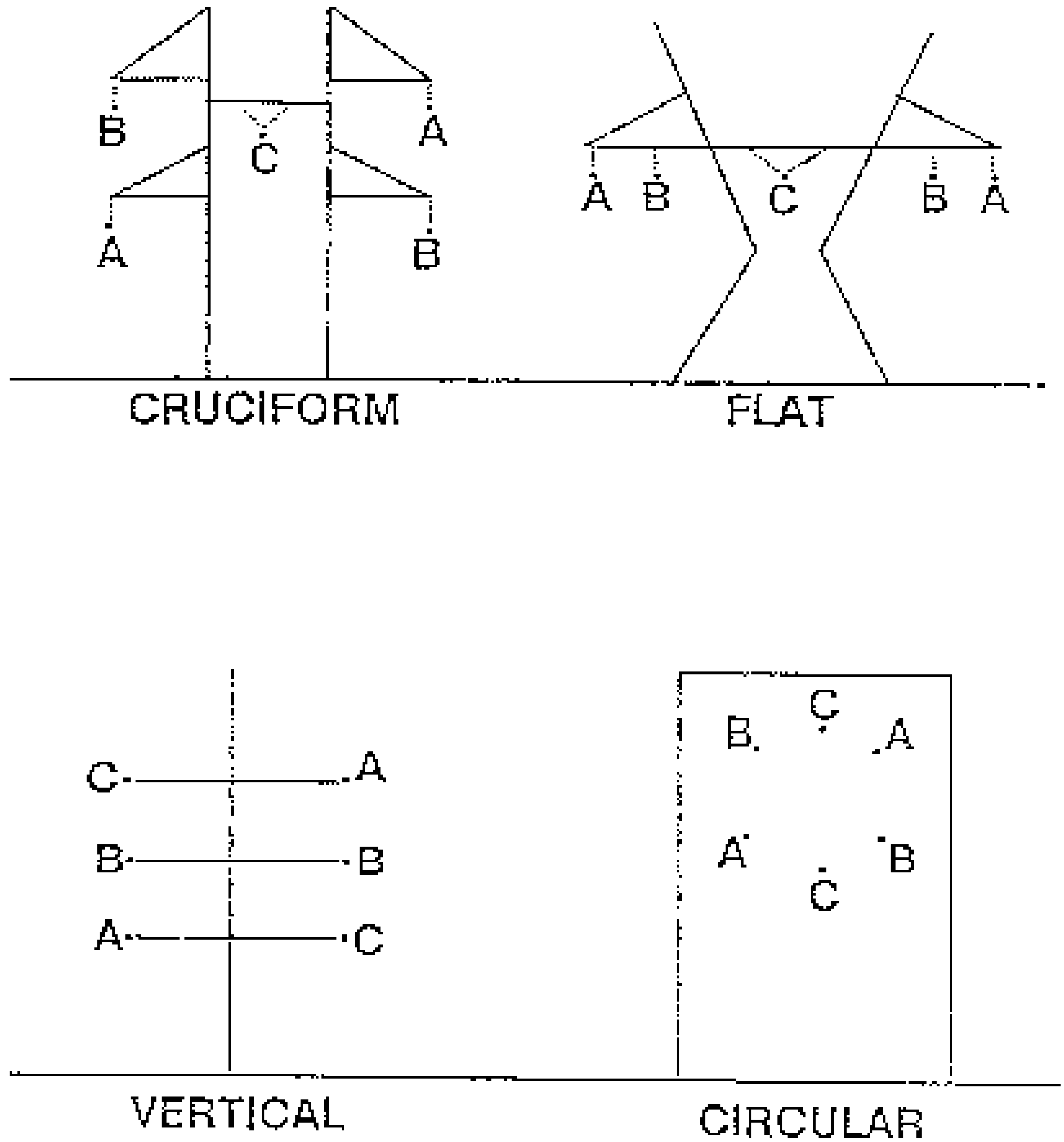


Figure 19
Split-Phase Transmission Lines

Applying the split-phase concept application to existing construction is difficult because of the constraints imposed by the conductor support structures on the line geometry, such as tower modifications to allow the change from single circuit to double circuit. This and another example which shows the addition of two conductors to existing lines of traditional design are shown in Figure 21. In this case, only two of the phases would be split. Even though the geometry is such that a pure quadrupole cannot be created, the component of the magnetic field can be reduced to a minimum by designing the additional conductors with an impedance to create an optimum current split. The field reduction in the distant field would still be substantial. The costs of these options would be significant, but it should be weighed against potentially significant costs of alternative solutions should magnetic field reduction be necessary.

It is important to note that the split-phase option can be applied as a local solution involving a limited number of spans. This issue may be relevant should certain areas traversed by the line be particularly sensitive to magnetic field exposure.

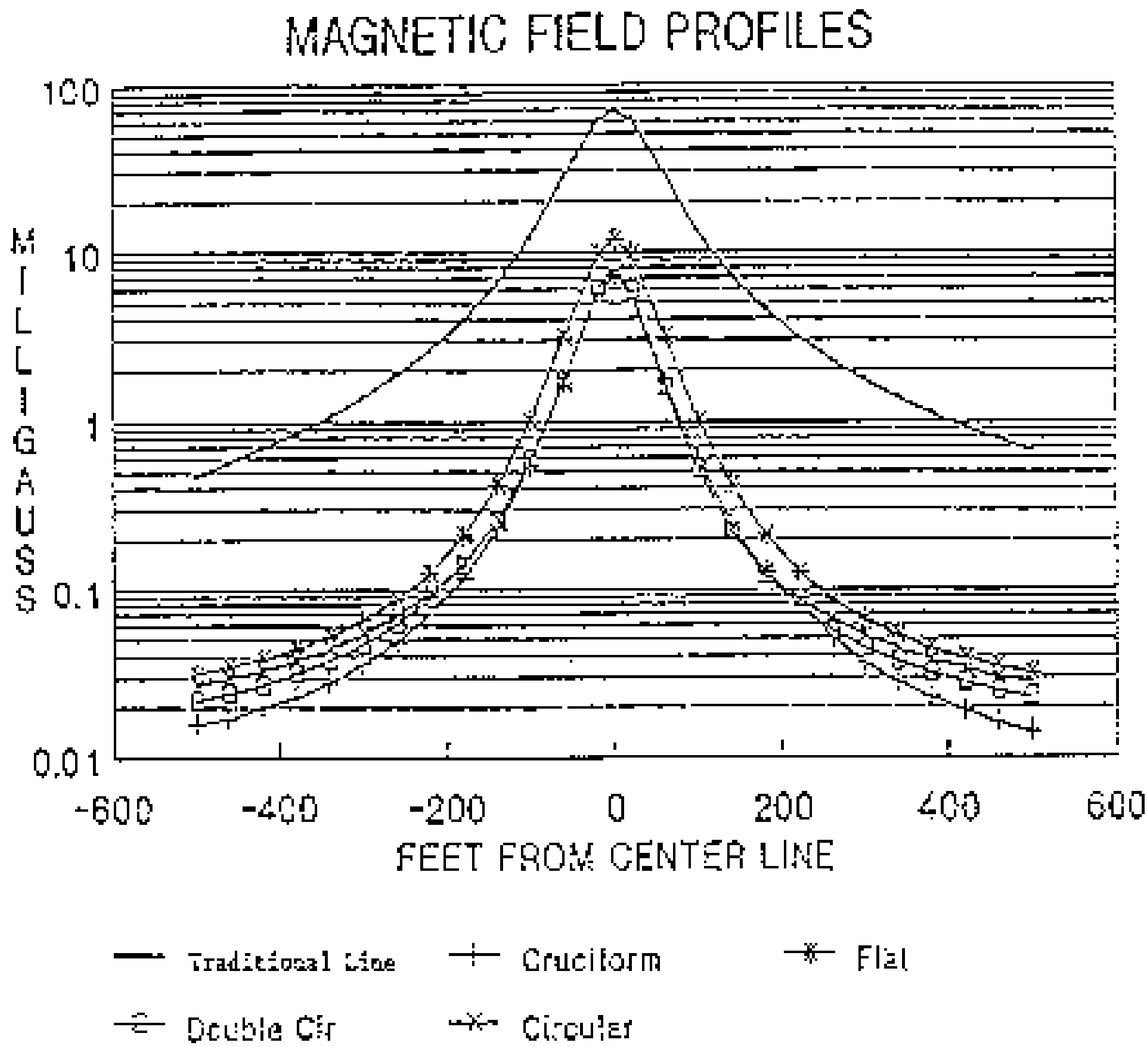


Figure 20
Split-Phase Lines Produce Much Lower Fields

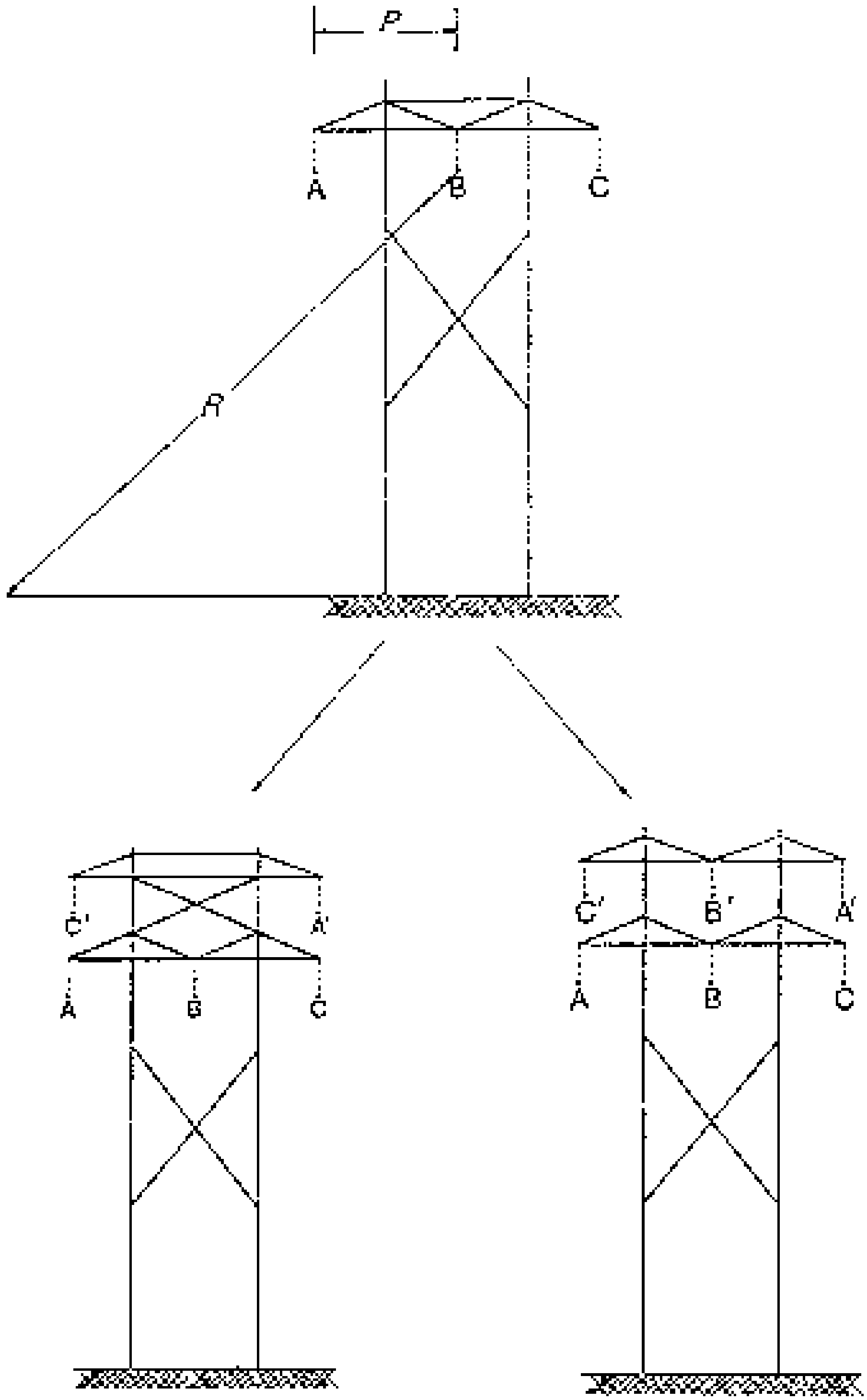


Figure 21
Split-Phase Modification to Existing 3-Phase Lines

Original configuration: $$B = 2 \cdot \sqrt{3} \frac{PI}{R^2}$$

Original configuration (left side): $$B = 1.2 \frac{PI}{R^2}$$

Modified configuration (right side): $$B = 4 \frac{P^2 I}{R^3}$$

An even greater distant field reduction can be obtained by splitting phases in more than two conductors. For instance, if phase A is placed in the center of the configuration and phases B and C are split in 3 conductors each, placed at alternative vertices of an hexagon surrounding phase A, the distant field is:

$$B = 1.5 \frac{IP^3}{R^4}$$

where: P is the phase-to-phase distance

The field is circularly polarized.

In this case, the field decays with the fourth power of the distance. The distant field reduction is dramatic. For instance, at R = 5P (R = 100 ft for P = 20 ft) the field would be about 2.5% of that produced by an equilateral delta 3-phase line, and at R = 10P (R = 200 ft for P = 20 ft) the field would be less than one percent of that of a traditional 3-phase line.

It must be noted that the split-phase design is not a proven technology and requires more analysis and demonstrations.

Configuration Twist

Significant magnetic field reduction can be obtained if the configuration is twisted with the phases helically wound around the configuration center. This is only a design concept and not a proven technology. Its effectiveness and practicality must be evaluated. Interphase spacers are needed to keep the phases from collapsing on each other. This is a severe technological limitation which may limit this option to distribution voltages and to transmission voltages $\leq$ 138 kV.

If the line currents have a dipolar component, each short segment of the lines produces a dipolar field, except that the fields produced by different line segments have different angles in space. The field obtained by integrating the contributions of each segment is lower than that with the conductors all parallel to each other. The general solution is:

$$B = 2 \cdot M \cdot \frac{f(A)}{R^n}$$

where:

A = (n-1)R/T

B = r.m.s. value of magnetic field (mG)

R = distance to helix center (m)

T = helix pitch (m)

M = value of the multipole

n = order of the multipole

f is the Helix Effect shown in the table below.

HELIX EFFECT					
A	f(A)	A	f(A)	A	f(A)
0.1	0.86	0.6	0.32	1.6	0.103
0.2	0.70	0.8	0.23	1.8	0.091
0.3	0.57	1.0	0.18	2.0	0.081
0.4	0.46	1.2	0.14	3.0	0.054
0.5	0.38	1.4	0.12	4.0	0.040

For equilateral triangular 3-phase configuration:

$M = \sqrt{6}\frac{PI}{2}$, n=2

For a flat 3-phase configuration:

M = $\sqrt{3}PI$, n=2

For a split-phase, circular configuration:

M = $\sqrt{6}P^2I$, n=3

As an example, assume a 3-phase line with triangular configuration, 3 meter phase spacing and a current of 1000A per phase and consider the following cases: the configuration is twisted with a 50 m helix pitch, the configuration is changed into a split-phase (cruciform configuration), and the split-phase configuration is twisted. The results are shown in table 4. The configuration twist has a dramatic effect, comparable to that achievable with a split-phase arrangement. If both techniques, split-phase and configuration twist, are combined, the distant field virtually disappears.

It must be noted that the results shown are derived from calculations. In practice, geometric imperfections and the presence of even small values of net currents, would prevent extreme field reduction. Also, the cost and practicality of these options must be evaluated.

Table 4 Field

Comparison Between Ordinary, Twisted, And Split-Phase Configurations P = 3m, I = 1000 A, T = 50m)

Distance from line (m)	Distance from line (ft)	Ordinary Line (mG)	Twisted Configuration (mG)	Split Phase (mG)	Twisted Split-Phase (mG)
25	82	118	4.5	2.0	0.76
50	164	3.0	0.53	0.25	0.04
100	328	0.75	0.06	0.03	0.003

SHIELDING

Shielding by Induced Currents

Additional conductors at or close to ground potential can be installed, parallel to the transmission line conductors, to reduce the distant field. With proper conductor arrangement and connections, the current flow into these shield wires would produce a field which partially cancels the transmission line field.

If effective, this concept would be suitable for existing lines and localized applications. Current flow in a loop of shield wires depends on the loop voltage induced by the transmission line conductors and on the loop impedance. The impedance of shield wires is determined by the wire resistance and inductance. In most applications, the inductance is the largest component of the impedance. To reduce the impedance, series capacitor compensation has been proposed. By appropriately selecting the capacitance, the shielding effect can be substantially increased.

The optimum placement of shield wires depends on the type of line configuration. For a horizontal configuration, the optimum arrangement consists of two shield wires, one on each side of the transmission line, near the edge of the right of way. For a vertical line configuration, the use of a loop involving a counterpoise and a shield wire above the phase conductors would produce more optimum results.

A more complex arrangement of shield wires is required to reduce the field of transmission lines employing a delta configuration.

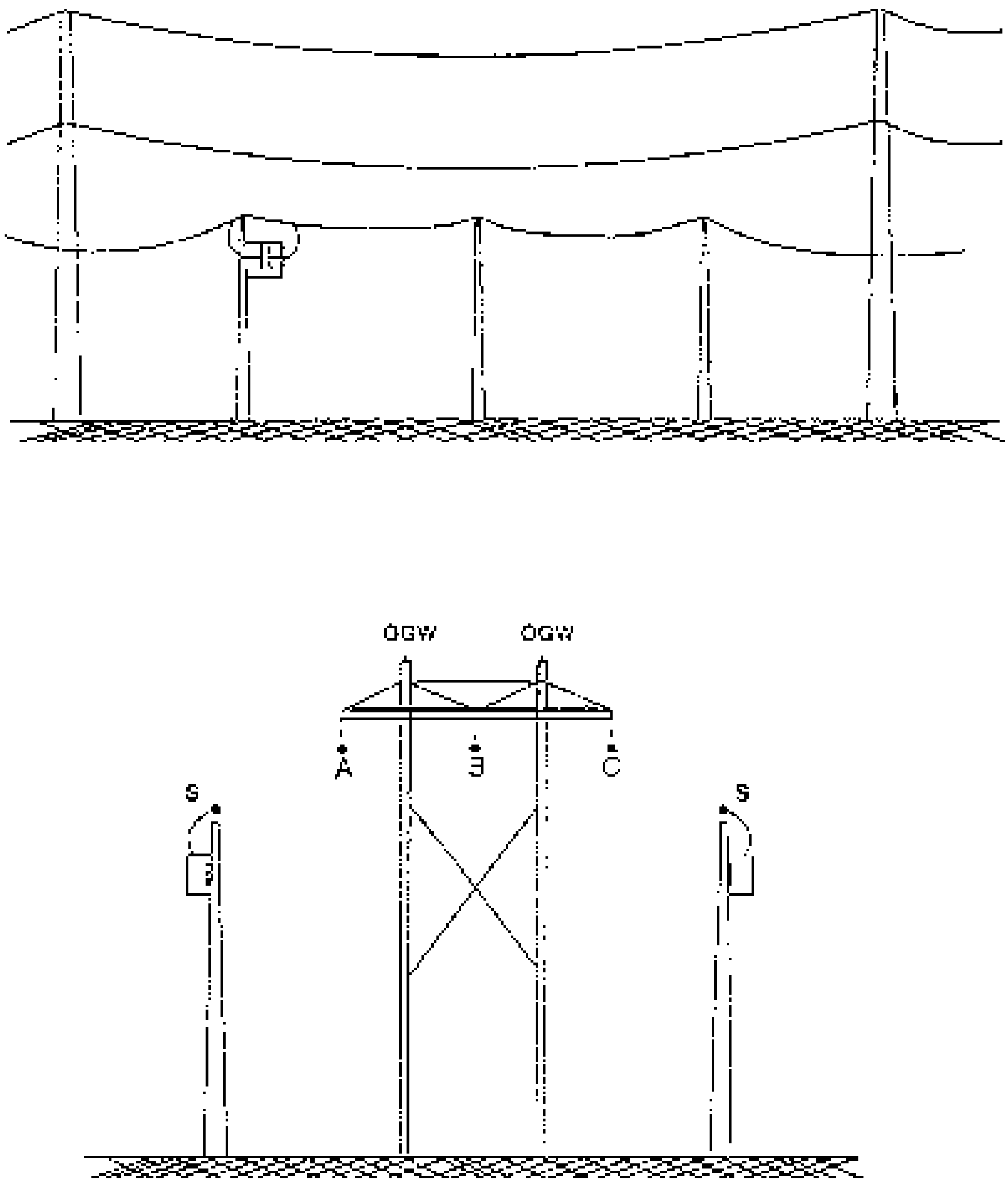


Figure 22
Shield Wires with Capacitor Compensation (A,B,C are the Phase Conductors. S is the Shield Wire, OGW are the Overhead Ground Wires for Lightning Protection

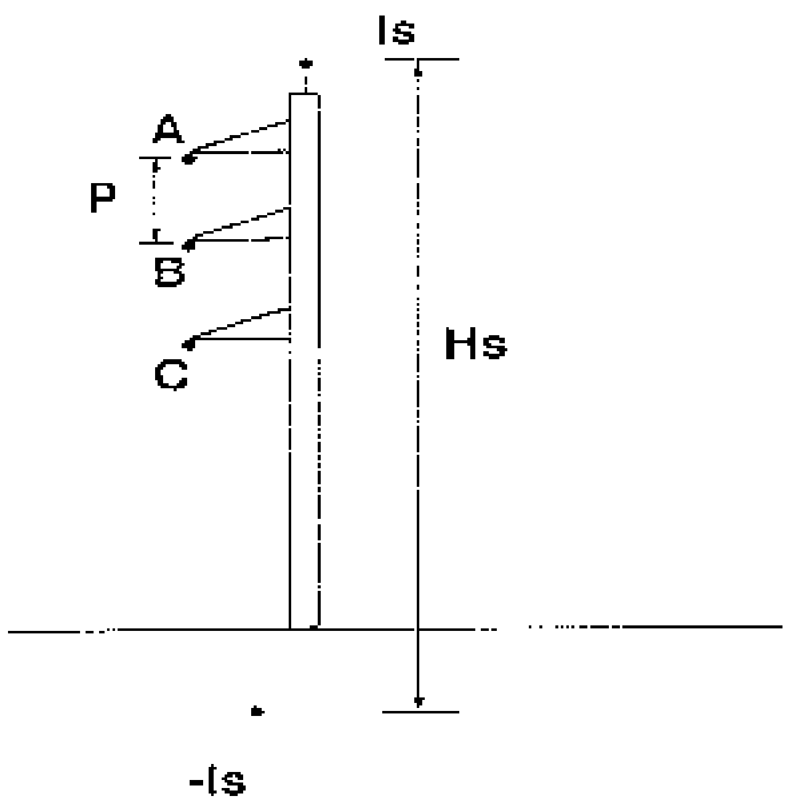


Figure 23
Shielding Wire Arrangement for a Vertical Line (Overhead Shield Wire and Counterpoise in Low Impedance Loop)

Active Shielding by Currents in Grounded Wires

In this approach, the field created by the transmission line conductors is canceled by creating an equal but opposite field. Using simply passive shield wires, even with an optimum shield wire arrangement and series capacitor compensation scheme, it may not be possible to achieve the desired shield wire currents. Imposing shield wire currents using external power sources represents a feasible engineering option. The power source would be controlled by a feedback circuit sensitive to the magnetic field measured at the locations to be shielded. The practicality of this option needs to be demonstrated.

Active Shielding by Other Lines

This is not a new concept, having been previously considered to reduce the electric field. An example of this application is underbuilding one or more lower voltage lines to a higher voltage line. The geometry of the lower voltage lines must be optimized to minimize the magnetic field. In a sense, this concept is similar to that of double circuit lines. Whenever several lines exist in the same corridor, their relative geometry and phasing can be optimized to minimize the magnetic field. The optimization process may yield a resultant magnetic field from all the lines in the corridor significantly lower than the magnetic field of the major line acting alone.

CONCLUSION

Much information is becoming available on the characteristics, methods of calculations, and measurements of the magnetic field of overhead transmission lines. Additional research on some of these factors is needed. There are several promising but yet unexplored engineering aspects of magnetic field management for overhead transmission lines.

REFERENCES

1. N. Wertheimer, E. Leeper, "Electrical Wiring Configuration and Childhood Cancer", Am. J.Epidemiology 109: 273-284, 1979.

2. D. Savitz, H. Wachtel, F. Barnes, "Case-Control Study of Childhood Cancer and Exposure to 60-Hz Magnetic Fields", Am. J. Epidemiology 108: 21-38, 1988.

3. S.J. London, D.C. Thomas, J.D. Bowman, E. Sobel, T.C. Cheng, J.M. Peters, "Exposure to Residential Electric and Magnetic Fields and Risk of Childhood Leukemia", Am. J. Epidemiology 131: 923-937, 1991.

4. Marie Feychting and Anders Ahlbom, "Magnetic Fields and Cancer in People Residing Near Swedish High Voltage Power Lines", Karolinska Institute, Sweden.