EXTREMELY LOW FREQUENCY ELECTRIC AND MAGNETIC FIELD MEASUREMENT METHODS

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INTRODUCTION

During the early 1970's, reports originating in the Soviet Union described a variety of ill effects experienced by personnel working in 500 kV and 750 kV switchyards [1,2]. The effects were attributed to the presence of the ac electric fields as well as to the occurrence of spark discharges between the workers and ground. At about the same time questions were raised regarding the possible environmental impact of high voltage transmission lines in the U.S. by the American author L.B.Young [3]. In response to the concerns generated by these and similar reports, numerous bioeffect studies with extremely low frequency (ELF) electric and magnetic fields were initiated in the U.S. by the Department of Energy [4], the Electric Power Research Institute, and during the early 1980's, the New York State Department of Health. The results of these and many newer studies which have focussed on magnetic field effects are now readily found in the technical literature. However, after more than 20 years of research, questions related to possible health effects from exposure to power frequency and other ELF fields remained unresolved. Evidence for the unresolved situation was given by Congress when it initiated an expanded 5-year research program which began in the early 1990's [5].

This paper focuses on the characterization of ELF magnetic and electric fields. Reliable characterization of these fields in the work place, residences, transportation systems, and in laboratory apparatus designed to simulate the fields (during biological studies) is essential if risk assessments are eventually to be performed. Because the mechanisms for effects reported in the literature are not yet understood, the question of what characteristics of the field constitutes the "dose" during exposure is also unresolved. One consequence of this uncertainty during field characterizations is the need to measure more than one parameter associated with the field. For example, in addition to measuring the magnitude of the field at a given location, measurements might also be performed to determine the polarization, temporal variation, frequency content, or time-weighted-average [6].

Following a brief description of ELF electric and magnetic fields, the types of field meters and their principles of operation will be surveyed. Consideration will be given to features necessary in the design of instrumentation to adequately characterize electric and magnetic fields with harmonics and fields which are highly nonuniform. Calibration techniques for magnetic field meters which are used to characterize fields over the dynamic range of a few nanotesla to about a millitesla will be noted. Measurement techniques in various environments as well as their limitations will also be briefly discussed and examples of measurement results in different environments will be presented.

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EXTREMELY LOW FREQUENCY ELECTRIC AND MAGNETIC FIELDS

While concepts of terms such as magnitude and frequency, as they are used to describe electric and magnetic fields are familiar to many readers, the concept of field polarization is perhaps less familiar. Single sources of magnetic fields consisting of currents in straight wires or loops of wire (one or more turns) can be represented at a point in space by a vector that oscillates in magnitude and direction along a straight line. Such fields are produced by some grounding systems and electrical appliances and are said to be linearly polarized. Multiple sources of magnetic fields, in which the currents are out of phase with respect to one another, can also be represented at a point in space with a vector. In contrast to the case of linear polarization, however, the vector rotates and in general traces an ellipse. For some conditions, the trace can be approximately a circle. Such fields are said to be elliptically or circularly polarized. Both types of fields have been used during *in vivo* and *in vitro* bioeffects studies.

Electric fields also can be linearly, elliptically or circularly polarized. The largest most likely encountered electric fields occur near ground level in the vicinity of power lines. Because the electric fields near ground level are approximately linearly polarized, such electric fields normally have been used for exposure purposes during bioeffects experiments.

The electric and magnetic fields of a three-phase transmission line have been calculated and illustrated by Deno [7] and a somewhat simplified sketch of the electric fields in the vicinity of a single-circuit three-phase transmission line is shown in Figure 1. Further discussion of ELF field polarization is provided in the IEEE standard for ELF measurement instrumentation, IEEE Std 1308-1994 [8].

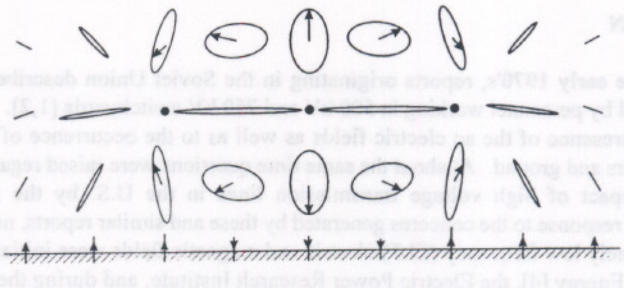

Figure 1. Electric field ellipses in the vicinity of a three-phase transmission line after Deno [7]. The phase of the power frequency voltage applied to each conductor differs by 120 degrees with respect to the other conductors. The electric field vector at a point in space rotates and traces an ellipse in the plane perpendicular to the conductors.

INSTRUMENTATION FOR MEASURING ELECTRIC AND MAGNETIC FIELDS

Electric Field Meters

Three types of electric field meters have been used to characterize power frequency and other ELF electric fields: free-body meters, ground reference meters, and electro-optic meters. Free-body meters are usually battery operated, electrically isolated from ground potential, and are supported in the field at the end of a long insulating rod. The magnitude of the alternating electric field is determined by measuring the induced current oscillating between two halves of an electrically isolated conductive body which makes up the probe or sensor. Figure 2 show geometries that have been used for commercial electric field strength meters. The free-body meter is suitable for survey-type measurements because it is portable, allows measurements above the ground plane, and does not require a ground reference.

Ground referenced meters are normally used with the probe or sensor located on grounded surfaces[1]. Ground reference meters determine the magnitude of the field by measuring the induced current to ground.

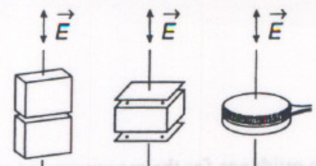

Figure 2. Geometries used for commercial free-body electric field meters.

Because the currents induced into the probes of free-body and ground referenced meters are proportional to the time-derivative of the electric field, the waveform of the current no longer reflects that of the electric field when harmonics are present in the field. That is, the contributions of the harmonics to the current will be weighted by the harmonic numbers due to the differentiation operation by the probe. Consequently, to avoid measurement errors, a stage of integration is often incorporated into the signal processing circuitry to recover the waveform of the field.

The underlying physics for performing measurements with electro-optic meters (typically Pockel's effect devices) differs from that of free-body meters, but both types of meters are used in a similar fashion. Further discussions of the various types of electric field meters and their principles of operation are found in reference [8].

Magnetic Field Meters

Magnetic field meters are available with single- and three-axis coil probes or sensors. Fluxgate magnetometers, capable of measuring the static and ELF magnetic fields, are also available with single- and three-axis probes. A schematic view of a simple magnetic field meter consisting of a single coil (or single-axis) probe and voltmeter detector is shown in Figure 3. The principle of operation is based on Faraday's law which predicts that a voltage proportional to the time-derivative of the magnetic field will be produced by the coil. As for free-body and ground referenced electric field meters, a stage of integration should be added to the signal processing circuit to avoid measurement errors when the field contains more than one frequency. While the simple device described in Figure 3 shows a single coil probe, there is increasing use of probes consisting of three coils which have their axes orthogonally oriented.

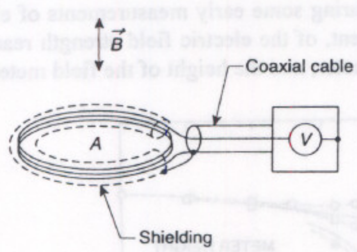

Figure 3. Design of simple magnetic field meter.

Although the devices described are useful for survey type measurements, for long term and more comprehensive measurement applications there is available three-axis instrumentation which periodically records the field level. The recorded values are normally downloaded to a personal

[1] A notable exception occurs when electric fields from video display terminals are measured in accord with requirements in an IEEE standard [9].

computer for analysis. Yet more sophisticated instrumentation which can simultaneously record periodically the waveform of the field in three orthogonal directions for later analysis is also available [10].

CALIBRATION METHODS

Electric Field Meters

Several standards exist which provide guidance for the measurement of power frequency and other ELF electric fields [8,11,12]. These standards describe the use of a parallel-plate apparatus for generating a known electric field for purposes of calibration. A nearly uniform electric field can be produced with parallel plates provided that the side dimensions of the plates are more than twice the plate spacing. Further details of the calibration process as well as verification of calibrations are discussed in the standards cited above.

Magnetic Field Meters

Calibration of magnetic field meters is normally done by introducing the probe into a nearly uniform magnetic field of known magnitude and direction. Helmholtz coils have frequently been employed to generate such fields, but the more simply constructed single loop of many turns of wire with a square geometry has also been used [8,11]. The simplicity in construction is at the expense of reduced field uniformity, but sufficient accuracy is readily obtained.

Establishing a known magnetic field for calibrating the more sensitive scales of a magnetic field meter (e.g., 0.2 μT range) is usually complicated by the presence of ambient fields that are of the order 0.1 μT. This problem can be overcome in some cases by using an alternative calibration technique known as voltage injection. With this approach, voltages corresponding to signals that are produced by small magnetic fields are injected into the detector circuit. Further details of this approach can be found in References [8] and [13].

SOURCES OF MEASUREMENT UNCERTAINTY

Electric Field Measurements

Effects of handle leakage, humidity, temperature, harmonic content in the electric field, observer proximity, and reading an analog display from a distance may all contribute to errors in measurements when electric fields are being characterized [8]. The effect of the observer's proximity to the field meter probe was not fully appreciated during some early measurements of electric field strength. Figure 4 shows the perturbation, in percent, of the electric field strength reading as a function of distance between the observer and field meter, and the height of the field meter above ground. The

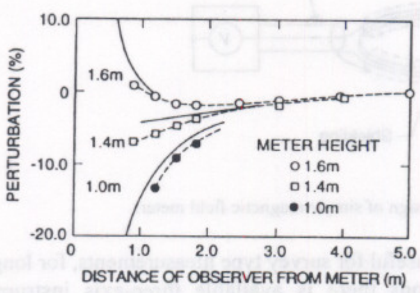

Figure 4. Perturbation due to a 1.8 m tall grounded observer as function of meter/observer distance and meter height above ground. Theoretical values are indicated with solid lines; dashed lines pass through measured values.

data points, which were obtained beneath a 500 kV transmission line, represent perturbations by a 1.8 m tall observer at ground potential and the solid curves are corresponding theoretical predictions

[14]. The perturbations depend markedly on both observer distance and field meter height. Other parameters which can introduce measurement errors are discussed in Reference [8].

Magnetic Field Measurements

The sources of error during measurements of magnetic fields are fewer than for the electric field case. Because there are no significant observer proximity effects, the observer can hold the field meter and thereby reduce errors due to reading an analog display from a distance (as during electric field measurements). However, consideration must be given to choosing the correct probe size when measuring nonuniform magnetic fields near their sources. Significant errors can occur when using circular coil probes because of averaging effects over the cross sectional area of the probe. Recently, calculations have been made of the error probability distributions when three-axis coil probes (with a common central point) and single-axis coil probes are used to measure dipole-like magnetic fields produced by some electrical appliances [15,16]. Figure 5 shows the probability distribution of measurement errors for a three-axis coil probe when the probe is positioned three probe-radii away from an appliance that can be approximated as a dipole (e.g., an electric shaver or hair clipper). The results can explain why two measurements made at the same point in space can differ by more than 30% if the orientations of the probes are different [15].

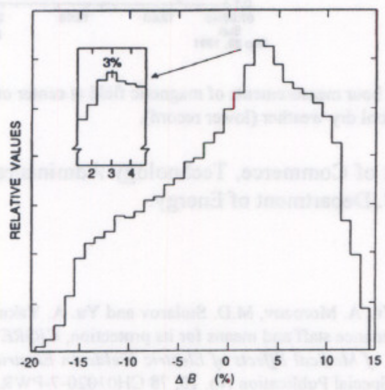

Figure 5. Probability distribution of measurement errors (ΔB) when three-axis probe is three probe-radii away from dipole magnetic field source. The inset shows an expanded view of the distribution near the most probable error.

MEASUREMENT UNCERTAINTY AND VARIABILITY

During measurements of magnetic fields, it is useful to distinguish between measurement uncertainties associated with calibration and instrument design, and uncertainties due to spatial and temporal variations. The uncertainties in the first category are normally associated with measurement accuracy and can be made small (e.g., <5%) by careful instrument design and calibration procedures. There is less control over the second category of uncertainty because the magnetic fields can have, for example in a residence, unknown spatial and temporal variations. The second category of uncertainty may be better referred to as measurement variability, distinct from measurement accuracy. Thus, while a spot measurement at some location may be performed with good accuracy, it will not be possible to specify with confidence what the variability will be without further measurements. Figure 6 shows 24-hour histories of the resultant magnetic field (i.e., root-mean-square of three spatial components) at the center of a living room on two days during which the load currents varied significantly because of weather conditions. The data were obtained with a three-axis meter that recorded the field at a height of 1 m above the floor. Figure 6 (top) shows measurements during a hot and humid July day in the metropolitan Washington area, when air conditioners were presumably in great use. The data were recorded every 15 seconds and the short-term variations, which could last as long as several minutes, could not be attributed to any known sources in the residence. Field measurements at the same location during a cooler, less humid day in September [Fig. 6 (bottom)], reveal a significantly different range of values with an average field of about one-half as large as that during the July observations. The anecdotal data shown in Figure 6 demonstrates that the temporal variability can exceed by far the uncertainties associated with the calibration process and field meter design.

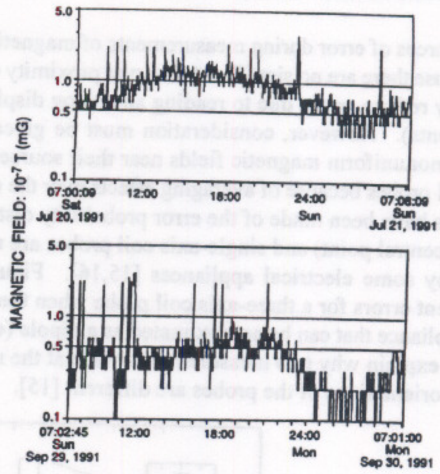

Figure 6. Twenty-four hour measurements of magnetic field at center of living room during hot and humid weather (upper record) and during cool dry weather (lower record).

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DISCUSSION

H. OKUBO: In the case of a power transmission line for the electric field there is no problem because the transmission-line voltage is almost constant. However, in the case of the magnetic field, the current flowing condition changes instantaneously like unbalance component of 3-ϕ current and so on. Could you please comment on this point?

A. BULINSKI: A general kind of impression is that the higher the voltage of the transmission line the more danger it is, i.e., the higher is the magnetic field it produces. However, a higher voltage transmission line is taller than a lower voltage line and it could be that the lower voltage rated line produces higher magnetic fields than the higher transmission line. Do you have any data on that? What about fields from underground lines?

M. MISAKIAN: The answers to the questions from Dr. Okubo and Dr. Bulinski overlap sufficiently that I shall give a single response.

Excellent discussions of magnetic fields from transmission lines and distribution lines (overhead and underground) are given in a paper prepared by a Task Force of the AC Fields Working Group in the IEEE Power Engineering Society. The reference is, "Magnetic Fields from Electric Power Lines - Theory and Comparison to Measurements," IEEE Transactions on Power Delivery, Vol. 3, pp. 2127-2136 (1988). Power frequency magnetic fields can be calculated using the law of Biot-Savart which predicts that the field decreases with distance from the source. As implied in the question from Dr. Bulinski, although distribution lines carry less current than transmission lines, the location of the conductors may be closer to where there is human activity, resulting in greater exposure. However, as will be evident from reading the above article, there are many other considerations when estimating exposure to magnetic fields, e.g., the magnitude and location of the return current, buried pipes, and the geometry of the energized conductors. Because of the temporal variation of magnetic fields in transmission and distribution lines, a statistical description of the field levels may be more informative as discussed in the Transaction paper. Local sources in residences such as electrical appliances and currents in metallic water pipes (used as connections to ground) can lead to higher background magnetic fields.

Depending on the measurement location, the magnetic field from buried conductors may be greater than from overhead lines carrying the same current. The shielding effectiveness of metal pipes used in underground power lines is described in a conference paper presented at the 1993 U.S. Department of Energy Conference on Electric and Magnetic Fields in Savannah, Georgia. The paper, "Reduction of Power Frequency Magnetic Field Emission Through the Use of Metallic Conduit," was presented by M. Major and D. March from Montana State University.

T. KAWAMURA: Do you have any experience and experimental data concerning the magnetic field environmental condition in the GIS transmission line and substation?

M. MISAKIAN: NIST does not have experience in characterizing magnetic fields from gas-insulated power lines or substations. A journal that would likely have articles related to this question is the IEEE Transactions on Power Delivery. For example, the article "Measurements and Computations of Electromagnetic Fields in Electric Power Substations," IEEE Transactions on Power Delivery, Vol. 9, pp. 324-332 and the references cited therein, would be of interest. Another recent article, entitled "Five Years of Magnetic Field Measurement," [IEEE Transactions on Power Delivery, Vol. 10, pp. 219-228 (1995)], may also be of interest as it includes measurements of magnetic fields from a variety of sources found in the electric power industry.

GASEOUS DIELECTRICS VIII

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