

MEASUREMENTS OF POWER FREQUENCY MAGNETIC FIELDS AWAY FROM POWER LINES

A Report of the IEEE Magnetic Fields Task Force* of the AC Fields Working Group of the Corona and Field Effects Subcommittee of the Transmission and Distribution Committee.

ABSTRACT

Recent epidemiological studies have focused attention on the measurement of ambient level power frequency magnetic fields in residential and industrial settings. These fields can be as much as two orders of magnitude smaller than power line magnetic fields and can also contain significant levels of harmonic content. Because the existing IEEE standard for characterizing power frequency magnetic fields is intended for measurements near power lines, it has a number of inadequacies if used alone for guidance during the measurement of residential fields. This paper describes the instrumentation, calibration procedures, and outlines measurement strategies which can overcome some of the shortcomings of the existing standard. Examples of ambient level magnetic field measurements are also provided.

Keywords: Power Frequency Magnetic Field Measurements, Residential and Industrial Magnetic Fields, Instrumentation, Ambient Fields, Calibration, Measurement Strategy.

1. INTRODUCTION

Questions raised in the early 1970's regarding possible adverse environmental effects due to high-voltage ac transmission line fields [1-3] focused attention on the need for accurate measurements of power-frequency electric and magnetic fields near power lines. Due in part to these early concerns, an ANSI/IEEE standard which provides guidance for measuring 60-Hz electric and magnetic fields near power lines was developed by the late 1970's [4]. Recent epidemiological studies have focused attention on the characterization of power-frequency magnetic fields in homes and in the workplace. These fields differ from the fields near power lines in two important respects: (1) the magnitude of the fields can be as small as 1×10^{-7} tesla (1mG ; $10^{-4}\text{G}=1\text{T}$) [5], which is about two orders of magnitude smaller than the fields near some power lines, and (2) the fields can contain large percentages of harmonics, e.g., in excess of 30% [6]. In addition, while the geometry and current characteristics of overhead

power lines can be fairly well defined, the same cannot be said for sources of magnetic fields in residential and occupational settings. Indeed, the geometry and magnitude of residential fields are typically more complicated and can depend on such factors as routing of distribution lines, number of local service drops, and type of ground return [5,7].

The above remarks suggest that instrumentation used for characterizing residential fields must have scales sensitive enough to measure fields of order 1×10^{-7} tesla and a frequency response that is appropriate for measuring the power-frequency harmonics. In addition, a calibration procedure that is not influenced by ambient magnetic fields should be used for the sensitive scales. (Note: The words "ambient magnetic fields" refer to all-encompassing fields which are made up of contributions from sources near and far.) The ANSI/IEEE standard noted above for measuring power line fields describes a calibration procedure using a coil system to produce a known field which is much larger than the ambient fields and therefore is not significantly perturbed by them. The standard also assumes that the harmonic content in the field is small, i.e., a few percent or less. Thus the standard has certain shortcomings if used alone as a guide for characterizing residential magnetic fields. The purpose of this paper is to provide information which can be used for some guidance during the measurement of residential and occupational power-frequency magnetic fields. However, it is noted that measurement protocols for characterizing residential magnetic fields are still under development. This paper describes the instrumentation, calibration procedures and some measurement techniques which can be used during measurements in residential as well as occupational and outdoor environments. Examples of measurement results obtained in the various settings are also provided.

2. INSTRUMENTATION

2.1 General Characteristics

Magnetic field meters used to measure power-frequency magnetic fields consist of two parts, the probe or field sensing element, and the detector which processes the signal from the probe. Magnetic field probes, consisting of electrically shielded coils of wire, have been used in combination with a voltmeter as the detector for survey type measurements of 60-Hz power line magnetic fields [4]. A schematic view of this kind of instrumentation, sometimes referred to as a survey meter, is shown in Figure 1. For measurements in a residential setting, where harmonic components in the magnetic field may not be negligible, an integrating amplifier is incorporated into the detector circuit in order to preserve the waveform of the magnetic field (see Section 2.2). During survey type measurements of the magnetic field, the probe can be held by hand without significant perturbation of the field due to the proximity of the observer. Proximity effects of nearby dielectrics and poor magnetic conductors are also insignificant. The rms field value is read from an analog or digital display. Typically, no provision is made for storage of data, although output connectors for commercially available recorders are sometimes provided.

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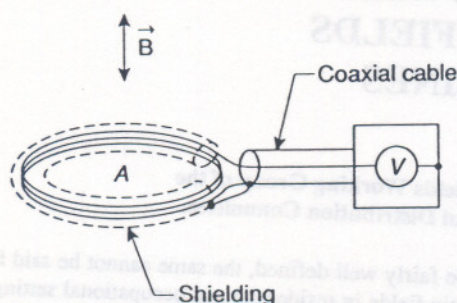


FIGURE 1. Schematic view of coil-type magnetic field meter used near power line.

For long term and more comprehensive measurement applications, the survey field type meter can be replaced with a larger and sometimes less portable measurement system containing three orthogonally oriented coil probes for simultaneous, continuous, measurements of the three spatial components of the field, and a commercial data storage system which permits later analyses of the measurements [7]. It should be noted that in general, vectorially summing the rms values of the three orthogonal components will not yield the maximum value of the magnetic field (i.e., the rms value of the magnetic field along the semi-major axis of the field ellipse) because of phase differences between the spatial components. However, an upper limit to the maximum field value is provided by this summation. It is also interesting to note that the rms value of the total magnetic field is equal to the vector sum of the rms values of the spatial components [7].

The development in recent years of small magnetic field personal exposure meters, devices which can be worn to continuously measure and record the spatial components of magnetic flux density, has also led to the use of miniature coil probes containing ferromagnetic cores for increased sensitivity [8]. Other types of field meters with high permeability inductor probes, such as the fluxgate magnetometer [9], have been used for measuring low level dc magnetic fields in such applications as mineral prospecting and measurements in interplanetary space [10], can be adapted for ac field measurements. It is noted, however, that the performance of fluxgate magnetometers, in the presence of ac and dc magnetic-fields of comparable magnitude, remains to be systematically tested.

Also available are magnetic field meters with Hall effect probes that can be used to measure magnetic flux densities from dc to several hundred hertz. However, Hall effect probes respond to the total magnetic field. Because of their low sensitivity and saturation problems due to the earth's magnetic field, they are not suited for residential or power line measurements. Therefore, this paper only considers instrumentation that employ, pick-up coil probes, with and without magnetic cores.

To characterize the harmonic content in the magnetic field, the detector signal (which reflects the waveform of the magnetic field) can be examined using commercially available spectrum analyzers to obtain the amplitudes of the fundamental and harmonic components. An alternative approach, again using commercially available instrumentation, is to digitize the detector signal waveform and use Fourier analyses to determine the amplitudes as well as phases of the fundamental and harmonic components.

Another option which is available for characterizing a magnetic field containing harmonics is to use a measurement system consisting of a detector without an integrating stage. The detector, however, is combined with instrumentation to digitize the signal waveform (which is proportional to the derivative of the magnetic field). By using Fourier analysis, the amplitude-enhanced harmonic components can be determined, and by dividing the harmonic component amplitudes by the harmonic number (using computer software), the correct harmonic percentages and their phase relations can be determined. This measurement approach allows for the recovery of higher order harmonics (e.g., ≥ 9 th harmonic) which may be lost, due to signal-to-noise problems, using an integrating amplifier.

2.2 Theory of Operation: Air Core Coil Probe

The principle of operation of the magnetic field meter shown in Figure 1 is based on Faraday's law which predicts that an electromotive force (emf) is produced at the ends of an open loop of wire placed in a changing magnetic field. Specifically, the emf is equal to the negative of the time-rate-of-change of the flux, Φ , through the loop,

$$\text{emf} = -\delta\Phi/\delta t = -\delta/\delta t \left\{ \int_A \vec{B} \cdot d\vec{A} \right\} \quad (1)$$

where \vec{B} is the magnetic flux density and \vec{A} is the area of the loop. If the magnetic field is free of harmonics, e.g., $\vec{B} = \vec{B}_0 \sin \omega t$, then

$$\text{emf} = -\omega B_0 A \cos \omega t, \quad (2)$$

where the angular frequency, ω , is 2π times the frequency and it is assumed that \vec{B} is perpendicular to the area of the loop. For N turns of wire in the loop, the emf given by Eq. (2) will develop over each turn and the total emf will be $-N\omega B_0 A \cos \omega t$. Equation (2) shows that the sensitivity of the probe increases with cross-sectional area.

If there are harmonics in the field, there will be an additional term on the right side of Eq. (2) for each harmonic. Because of the differentiation operation in Eq. (1), each of the additional terms will be weighted by an associated harmonic number. For example, if there was 10% third harmonic in the field, the term, $-3 \times (0.1) \omega B_0 A \cos 3\omega t$, would be added to the right side of Eq. (2). (It should be noted that the ω 's in each term are the same.) Because of the weighting of the harmonic term, the waveform of the signal will no longer reflect the waveform of the field. Consequently, the rms value indicated by the voltmeter-detector (Figure 1) will not accurately represent the rms value of the field. The waveform does reflect, to a good approximation, the voltage or current induced in some biological systems.

To recover the magnetic field waveform, it is necessary for the detector to perform the inverse mathematical operation, namely integration. This can be accomplished by introducing an integration stage in the detector. For example an integrating amplifier combined with a voltmeter could be used as the detector. The frequency response of the probe-integrating amplifier combination can be made flat for the power-frequency harmonics. It should be noted that this "corrective" action provided by the detector is essential to obtaining accurate rms values of the magnetic field as well as correct percentages of harmonics.

Neglected in the discussion so far is the frequency response of the probe. Because of the inherent inductance, resistance and capacitance of the probe, the relationship between the emf produced in the coil [Eq. (2)] and the voltage entering the detector should be considered as a function of frequency. A schematic view of the equivalent circuit for the coil probe is shown in Figure 2. The ratio, $|A|$, of probe voltage, v_p , to emf is given by [11]

$$|A| = |v_p / \text{emf}| = \left\{ \left[(R + r) / R - \omega^2 LC \right]^2 + \left[\omega(L/R + Cr) \right]^2 \right\}^{-\frac{1}{2}} \quad (3)$$

where L and r are the inductance and resistance of the coil and its leads, C is the stray capacitance, and R is the approximate input impedance of the detector.

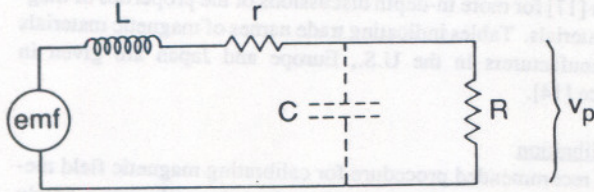


FIGURE 2. Equivalent circuit of coil-type magnetic field probe. R is the approximate input impedance of the detector.

The value of $|A|$ should remain close to unity and not peak before falling off with increasing frequency. Higher values of R cause peaking and a sharp fall-off in $|A|$, a possible cause of oscillation in some circumstances. Lower values of R permit the value of $|A|$ to roll off gently with increasing frequency. Too low a value, however, causes unnecessary reduction in frequency response [6]. Examples of plots using Eq. (3) for a coil probe and for different values of R are shown in Reference [6].

In the above discussion, it is assumed that the induced current in the coil probe, after it is connected to the detector, is sufficiently small that the opposing magnetic field produced by it is negligible.

Yet another consideration in the design of a detector is whether the detector indicates an "average rms" or true rms value of the field. If there are harmonics in the magnetic field, an average-sensing rms detector will be in error, the magnitude of which will depend in part on the magnitude and phase relations of the harmonics to the fundamental [4,12] (see Section 2.4).

Field meters have been developed which contain narrow band filters in the detector circuit. Depending on the band width of the filter, however, such instrumentation will be unable to measure contributions to the field of some or all of the power frequency harmonics, if present.

To minimize fluctuations of the field meter reading on the more sensitive scales due to movement of the probe in the earth's magnetic field, a low frequency cut-off (i.e., ≤ 40 Hz) can be incorporated into the detector circuit. However, such a feature could prevent accurate measurements of magnetic fields due to some electrical equipment which operate at lower frequencies, e.g., electric streetcars.

2.3 Theory of Operation: Magnetic-Core Coil Probe

As noted earlier, the use of miniature coil probes in exposure meters has led to the use of cylindrical ferromagnetic cores to increase the flux density through the coil, thereby increasing the sensitivity of the probe. The emf from the coil is still predicted by Faraday's law. Further, the discussion in Section 2.2 regarding the use of an integrating amplifier and probe frequency response is again applicable. In this section, the influence of the core permeability and core shape on probe characteristics are examined briefly. For purposes of discus-

sion, the coil probe with a cylindrical core in a uniform power-frequency magnetic field, \vec{B}_0 , is simulated by replacing the cylinder with a prolate ellipsoid as shown in Figure 3. While, unlike the cylinder, use of an ellipsoid leads to a uniform B field inside the core, the general conclusions indicated below are still valid.

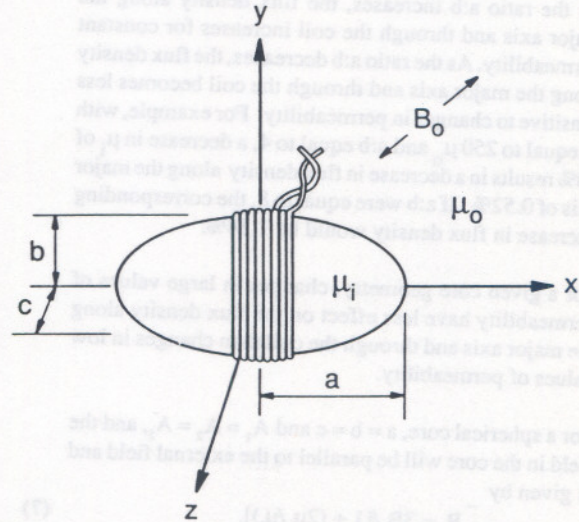


FIGURE 3. Geometry for coil-type probe with prolate ellipsoidal core of magnetic material. For clarity, the electrical shielding for the coil is not shown.

Expressions for the components of the magnetic flux density inside a prolate ellipsoid can be derived from an expression for the magnetic potential provided by Stratton [13]. The magnetic field components in Cartesian coordinates are

$$B_x = B_0 \alpha [a + b(1 - \alpha) A_1], \quad (4) \quad \alpha \equiv \lambda$$

$$B_y = B_0 \gamma [a + b(1 - \alpha) A_2], \quad (5) \quad \gamma \equiv b$$

$$B_z = B_0 \beta [a + b(1 - \alpha) A_3], \quad (6)$$

where $\alpha = \mu_i / \mu_0$, μ_0 is the permeability of vacuum, μ_i is the initial permeability of the core, $\beta = abc/2$, a is the semi-major axis of the prolate ellipsoid, b and c are equal and are the semi-minor axes. A_1 , A_2 and A_3 are elliptic integrals of the second kind and are given by

$$A_1 = \int_0^\infty \frac{ds}{(s + a^2) \left[(s + a^2)(s + b^2)(s + c^2) \right]^{\frac{1}{2}}}$$

$$A_2 = \int_0^\infty \frac{ds}{(s + b^2) \left[(s + a^2)(s + b^2)(s + c^2) \right]^{\frac{1}{2}}}$$

$$A_3 = \int_0^\infty \frac{ds}{(s + c^2) \left[(s + a^2)(s + b^2)(s + c^2) \right]^{\frac{1}{2}}} = A_2$$

and

The sinusoidal time dependence of the magnetic field in Eqs. (4) to (6) has been suppressed. As anticipated, Eqs. (4) - (6) show that the magnetic field in the ellipsoid is uniform, and in addition, generally not in the same direction as the external field. It is readily shown that as the ellipsoid is rotated in space, the flux density along the major axis, B_x , obeys the cosine law.

From Eqs. (4) - (6), the following observations, which may have relevance when designing a probe, can be made:

For a given core geometry, the flux density through the core and coil increases with permeability, as expected.

As the ratio $a:b$ increases, the flux density along the major axis and through the coil increases for constant permeability. As the ratio $a:b$ decreases, the flux density along the major axis and through the coil becomes less sensitive to changes in permeability. For example, with μ_i equal to $250 \mu_0$ and $a:b$ equal to 4, a decrease in μ_i of 10% results in a decrease in flux density along the major axis of 0.52%. If $a:b$ were equal to 8, the corresponding decrease in flux density would be 1.34%.

For a given core geometry, changes in large values of permeability have less effect on the flux density along the major axis and through the coil than changes in low values of permeability.

For a spherical core, $a = b = c$ and $A_1 = A_2 = A_3$, and the field in the core will be parallel to the external field and is given by

$$B_i = 3B_0 / [1 + (2\mu_0/\mu_i)] \quad (7)$$

Equations (4) - (7) have been derived assuming that the ellipsoid material is isotropic, homogeneous, free of residual magnetism and has a constant permeability. These assumptions are approximately satisfied by soft magnetic materials near room temperature in ambient fields, with normal handling. However, the following general information should be remembered when core materials are considered:

The core material should have a low coercive field to minimize the possibility of permanently magnetizing the core and changing the permeability if exposed to strong magnetic fields, i.e., the material should be soft.

Vibrations and the mechanical shock of dropping the core material can change the boundaries of magnetic domains and decrease the permeability, particularly if the initial permeability is high.

For sheet and strip material, the permeability decreases as the inverse-square-root ($f^{-1/2}$) above a critical frequency, f_c . For *sheet* material, f_c is given by [14]

$$f_c = 4\rho/\pi\mu_i D^2 \quad (8)$$

where ρ is the resistivity, μ_i is the initial permeability and D is the thickness of the sheet. The apparent decrease in permeability is due to opposing fields in the material caused by eddy currents. Thus, while high initial permeability is desirable for increasing the probe sensitivity, it reduces the value of f_c . Because of their high resistivities, ferrites can have very high values for f_c .

The initial permeability depends on many factors including chemical composition as well as mechanical and thermal treatment. For example, adding a few percent of silicon to soft iron increases the permeability, decreases the coercive field, increases the resistivity and

improves the stability of the magnetic characteristics [15].

The permeability of magnetic materials varies with temperature and the temperature coefficient depends on magnetic field strength as well as type of magnetic material [16].

The interested reader is encouraged to read texts by Heck [14] and Bozorth [17] for more in-depth discussions of the properties of magnetic materials. Tables indicating trade names of magnetic materials and manufacturers in the U.S., Europe and Japan are given in reference [14].

2.4 Calibration

The recommended procedure for calibrating magnetic field meters used near ac power lines is to introduce the probe into a nearly uniform magnetic field of known magnitude and direction [4]. Helmholtz coils have frequently been employed to generate such fields but the more simply constructed single loop of many turns of wire with rectangular geometry can also be used. The simplicity in construction is at the expense of reduced uniformity, but sufficient accuracy is readily obtained for single probes used with survey meters [18]. The z -component of the magnetic flux density at a point $P(x,y,z)$ produced by a rectangular loop of dimensions $2a \times 2b$ is given by the expression [19]

$$B_z = \frac{\mu_0}{4\pi} IN \sum_{\alpha=1}^4 \left\{ \frac{(-1)^\alpha d_\alpha}{r_\alpha(r_\alpha + (-1)^{\alpha+1} C_\alpha)} - \frac{C_\alpha}{r_\alpha(r_\alpha + d_\alpha)} \right\} \quad (9)$$

where

$$\begin{aligned} C_1 = -C_4 = a + x & \quad r_1 = \sqrt{(a+x)^2 + (b+y)^2 + z^2} \\ C_2 = -C_3 = a - x & \quad r_2 = \sqrt{(a-x)^2 + (b+y)^2 + z^2} \\ d_1 = d_2 = y + b & \quad r_3 = \sqrt{(a-x)^2 + (b-y)^2 + z^2} \\ d_3 = d_4 = y - b & \quad r_4 = \sqrt{(a+x)^2 + (b-y)^2 + z^2} \end{aligned}$$

N is the number of turns, I is the current and μ_0 is the magnetic permeability of vacuum. The coordinates x , y and z are shown in Figure 4. It is noted for purposes of reference that $B_z(0,0,0) = \mu_0 IN\sqrt{2}/\pi a$ for a square loop of side dimension $2a$. The uniformity of the field in the central volume of a $1m \times 1m$ loop is described in References [4] and [18], and is normally adequate for probes with diameters less than $\sim 10cm$. Therefore, the existing recommended procedures can be used for calibrating the higher ranges (i.e., $\sim 0.1 \times 10^{-4}$ to 1×10^{-4} tesla) of survey meters which are to be used for measuring residential fields.

By varying the frequency of the current through the loop (Fig. 4), the frequency response of the field meter can be determined for the power-frequency harmonics. For nearly constant $|A|$ [Eq.(3)] and a suitably designed integrating amplifier, a field meter with an air core probe should indicate a nearly constant rms value as the frequency is varied. A similar result should be obtained with a probe that contains a core of soft ferromagnetic material, if the change in permeability as a function of frequency is negligible. It is noted that while a flat frequency response may be observed with average-sensing rms detectors and true rms detectors, the response of the average sensing rms

detector to a complex magnetic field waveform consisting of the fundamental and one or more harmonics may still be in error [12].

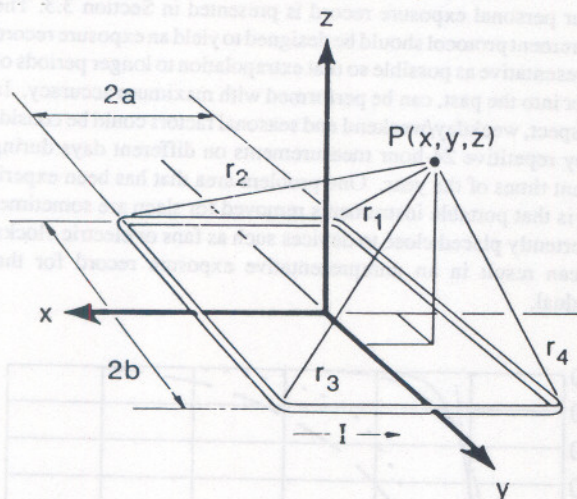


FIGURE 4. Coordinate system of rectangular loop for generating known magnetic field, B_z , for calibration purposes.

Establishing a known magnetic field for calibrating the more sensitive scales (i.e., $\sim 0.10 \times 10^{-7}$ to 0.1×10^{-4} tesla) is made difficult by the presence of ambient fields of order 1×10^{-7} tesla. This problem can be overcome by using an alternative calibration technique, that of voltage injection. From Eqs. (2) and (3), it is seen that, the probe voltage, v_p , is a linear function of B , for constant $|A|$ using an air core probe. Therefore, the ratio $v_p : B$ can be determined with a known B -field at field levels not significantly affected by ambient fields, and known voltages at frequencies of interest can be injected into the detector to calibrate the more sensitive scales. The ratio $v_p : B$ is determined with the probe connected to the detector. A voltage divider can be used to produce the typically small voltages necessary to calibrate the more sensitive scales. Adequate electric field shielding should be provided when calibrating the sensitive scales. The voltage injection technique can be used with probes containing soft ferromagnetic cores assuming the change in permeability as a function of flux density is negligible. Further details of the voltage injection calibration technique can be found in Reference [6].

Air core probes in large measurement systems with more than one probe can be calibrated individually following the procedures for survey meters. This assumes that the electronic circuits associated with the detectors and data storage do not generate significant levels of noise which can be sensed by the detectors, particularly on the more sensitive scales.

If the probes contain magnetic cores and are in close proximity, as in the case of some miniaturized field exposure meters, the field sensed by one probe may be significantly perturbed by the core material of an adjacent probe. Similar proximity effects can occur due to other nearby magnetic materials (e.g., some battery cases.) Therefore, when the higher scales are calibrated with a known field to determine the ratio $v_p : B$, the entire instrument, appropriately aligned, should be placed in the field as each probe and associated detector is calibrated. Another possible impact of the field perturbation is the departure of the probe response from the cosine law. This possibility can be checked by rotating the instrument in the magnetic field. Depending on the size of the exposure meter, it may be necessary to increase the dimensions of the square loop of wire to increase the

volume of field uniformity, or alternatively generate the field with a sufficiently large Helmholtz coil system [20].

The close proximity of the probe, detector, and data storage circuits can make the problem of electrical noise pick-up more serious in small exposure meters than in larger measurement systems. The electrical noise can create a "noise floor" which prevents magnetic field measurements below a certain level. The minimum detectable field can be estimated by comparing measurements obtained with an exposure meter and a survey meter at locations where the ambient fields are unusually low. A more efficient approach would be to establish a very low ac magnetic field environment using magnetic shielding and make comparative measurements in this "zero" field. Reconfiguring circuit elements and adding magnetic shielding to circuit boards are possible steps to minimize the coupling of electrical noise to the probes as well as detector circuits. To date, no recommended noise floor has been established for instrumentation used for residential measurements.

3. MEASUREMENT TECHNIQUES IN DIFFERENT ENVIRONMENTS

As noted earlier there are no established protocols at this time for characterizing ambient magnetic fields in environments away from power lines. The more comprehensive the measurement goals are away from the power lines, however, the greater will be the measurement requirements. For example, the amount of information provided by a spot measurement of the rms value of the magnetic field at one location in a residential or industrial setting can be rather limited. No information is gained regarding the temporal variation of the magnetic field over periods of a day, a week, or across seasons. No information is obtained regarding the harmonic content in the magnetic field. The spatial variation of the field in the vicinity of the measurement point is also unknown and difficult to predict.

Because of the increased interest in characterizing residential magnetic fields in recent years, this subject is considered first. Different measurement strategies, which depend on the goals of the measurement program, are outlined. In the remaining sections, examples of measurement results obtained with several of the types of instrumentation described earlier are presented.

3.1 Residential Magnetic Field Measurements

Residential magnetic field environments can be quite complex. Only recently have researchers obtained data that can be used to better understand this environment [5, 7, 21, 22, 23, 24]. Large spatial and temporal variability renders residential magnetic fields difficult to characterize in any simple way. It is doubtful that a single measurement protocol can fulfill the needs of all possible types of research projects involving residential measurements. To a large extent, the measurement techniques employed will depend on the study goals. For all these reasons, no standard measurement protocol exists for residential magnetic field measurements.

However, this situation leads to a lack of comparability of data set among investigators. This invites confusion interpreting the results of the various studies. A goal of the Working Group of the IEEE is to develop a procedure which would at least present conditions to be met when collecting data for general reference purposes. In the interim, investigators are encouraged to characterize as much background information regarding the conditions that existed during their measurements to permit readers of their report to judge the comparability of the data.

This section of the paper will outline some representative study goals and the residential measurement techniques that could be used to address each of these goals.

There are two general classes of magnetic field measurements that can be made in a home:

1. Measurements at (possibly many) fixed space-time points in a residence. These house-oriented measurements can be classified as spot or area measurements.
2. Measurements of the exposure of persons living in the residence.

The most obvious use of area-type measurements is to identify and characterize magnetic field sources in homes. Source characteristics that can be studied with area measurements include spatial and temporal variability, relative strengths and prevalences, and harmonic generation. Another potential application of area-type measurements is the development of mitigation strategies.

Personal exposure measurements are usually a component of a larger study that may include an evaluation of health endpoints. Because of the spatial and temporal variability of residential magnetic fields, these measurements must in some explicit or implicit way factor in the behavior of the persons whose exposure is being assessed.

Personal exposure and area measurements may be related: that is, the purpose of house-oriented measurements could be to serve as a surrogate for actual personal exposure measurements [24]. At this time, the relationship between house measurements and total personal exposure is unknown.

3.1.1 Area Measurements

These are usually investigative measurements of a research nature to better understand field sources and characteristics. These measurements could also be used: to establish baseline field levels for some future powerline construction project; to evaluate mitigation strategies; to prepare for litigation; and as a surrogate for personal exposure. The measurements can range from simple point-in-time or spot measurements [25, 26] to fixed site monitoring of various locations in the home over an extended period [5, 7]. The advantage of the additional temporal information provided by fixed site monitoring can be seen in Figure 5. This figure presents the cumulative frequency distributions for fixed site time-series measurements collected in 5 homes during a 24-hour period [5]. The measurement device in this study recorded magnetic field values every 7 seconds. For certain magnetic field measurement goals, these distributions may more accurately characterize a home than a single space-time measurement at a location such as the front porch [26]. These curves express the percent of time ("Cumulative Percent") that the magnetic field intensity is below a given level ("Magnetic Field mG"), e.g., for Home 1, there is less than 2 mG 70% of the time.

3.1.2 Personal Exposure Measurements

Personal exposure measurements will usually require that a portable measurement instrument be carried by the person during a discrete exposure period—often 24 hours. This measurement approach gives an exposure record that directly takes into account the

time-location-activity behavior of the subject. These measurements can encompass exposure locations other than the home environment to give a more complete assessment of total exposure. An example 24-hour personal exposure record is presented in Section 3.3. The measurement protocol should be designed to yield an exposure record as representative as possible so that extrapolation to longer periods of time, or into the past, can be performed with maximum accuracy. In this respect, weekday/weekend and seasonal factors could be considered by repetitive 24-hour measurements on different days during different times of the year. One problem area that has been experienced is that portable instruments removed for sleep are sometimes inadvertently placed close to devices such as fans or electric clocks. This can result in an unrepresentative exposure record for that individual.

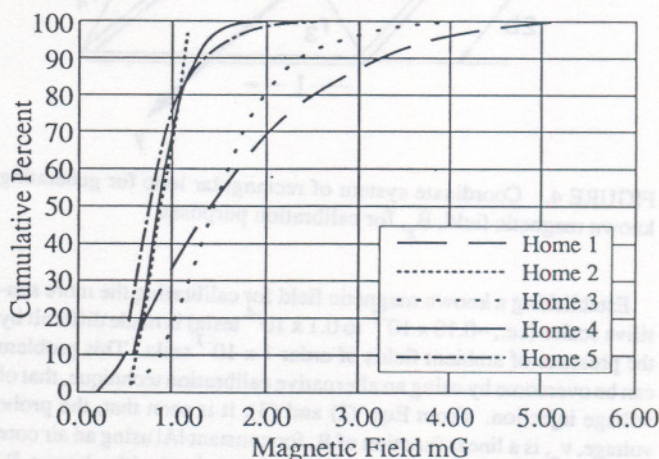


FIGURE 5. Cumulative frequency distribution for time series magnetic field measurements.

3.1.3 Measurement Techniques and Goals

Below is a listing of measurement techniques that can be used in a residential setting:

1. Spot and Area Measurements
 - a. At one point in space-time
 - b. A series of spot measurements in several rooms (possibly replicated for High/Low home power use and/or different days or seasons).
2. Lateral profiles from external power line sources into the home [4].
3. Peripheral profiles around outside boundaries of the home.
4. Fixed Site Monitoring—time series measurements (24-168 hr) at one or more fixed locations-bedroom, living room, etc.
5. Personal Exposure Measurements
6. Measurements of Harmonic Content

The following Table I summarizes some measurement techniques that could be used for different study goals.

Table I. Study Goals and Associated Measurement Techniques

Study Goal	Measurement Techniques
1. Provide "coarse" ranking of homes for epidemiology study.	<ul style="list-style-type: none"> • Single measurement at one location • Spot measurements of resultant field in several rooms - averaged to single value to represent the home. • 24 hr fixed site monitoring in one or more rooms.
2. Provide reasonably accurate ranking of homes for epidemiology study.	<ul style="list-style-type: none"> • 24-168 hr fixed site monitoring in several rooms, repeated for weekends and in different seasons. • Personal exposure measurements.
3. Source Characterization	<ul style="list-style-type: none"> • 24-168 hr fixed site monitoring coupled with "real-time" spot measurements for detection and evaluation of possible sources. • Harmonic content measurements.
4. Personal Exposure	<ul style="list-style-type: none"> • Subject wears personal exposure meter. • Fixed site monitoring at multiple points in residence. Use time-location-activity data and measurements to estimate personal exposure.

3.2 Residential Measurement Near Appliance

Measurements of the maximum 60-Hz magnetic field near many appliances as a function of distance from the appliances has been reported by Gauger [27]. Because magnetic fields from home appliances can contain significant levels of harmonic content and because laboratory studies have shown that some magnetic field bioeffects are a function of frequency [28], it is relevant to determine the harmonic content in the field. Figure 6 shows a spot measurement of the ELF magnetic field waveform 60 cm from the front center of an operating 26-inch television screen [6]. The waveform in Figure 6 is an oscilloscope display of the output signal from a survey-type meter consisting of a single axis air core probe about 9 cm in diameter and a detector containing a stage of integration. The probe was oriented to give the maximum field value and the oscilloscope was located about 6 meters from the measurement location to avoid perturbation of the field from the television. The rms value of the field is $0.17 \mu\text{T}$ (1.7 mG).

The harmonic components in the magnetic field are shown in Figure 7 which is the spectrum analyzer display for the waveform in Figure 6. Harmonic components from the second, which amounts to 47% of the fundamental, to nineteenth can be discerned. For this example, measurement of the magnetic field with a field meter that detected only the fundamental component would yield an rms value that would be too low by more than 20%. Because magnetic fields from appliances are usually highly nonuniform with ill-defined geometries, measurements of the field as a function of position would be required to determine the spatial variation of the field. It should also be noted that during measurements of nonuniform fields, the signal from the probe represents an average field value over the area, A, of the probe (Figure 1).

There is no standardized technique for measuring magnetic fields from appliances. This is in part responsible for the wide ranging values reported in the literature for appliances. As noted above, the complex field geometry, the harmonic content of the field, the influence of the measuring device to accurately assess the field all serve to complicate the situation. In the interim, while standardized procedures are being developed, the investigators should report at least (1) the distance between the appliance and the measurement sensor, (2) the frequency bandwidth of the measurement device and (3) if the reported data is a maximum, at the distance noted, or an *average* at that distance.

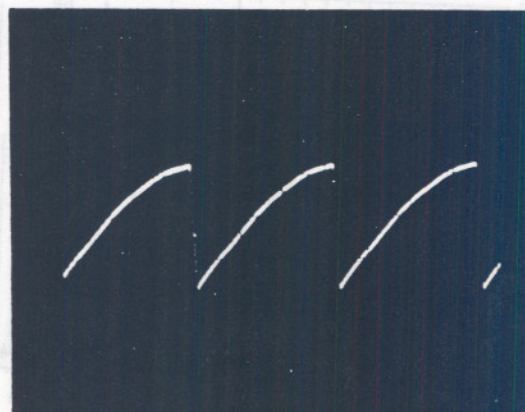


FIGURE 6. Oscilloscope display of magnetic field waveform obtained in home, 60 cm from the front center of an operating 26-inch screen television. The rms value of field is $0.17 \mu\text{T}$. Vertical scale = $0.2 \mu\text{T/div}$. Horizontal scale = 5 ms/div .

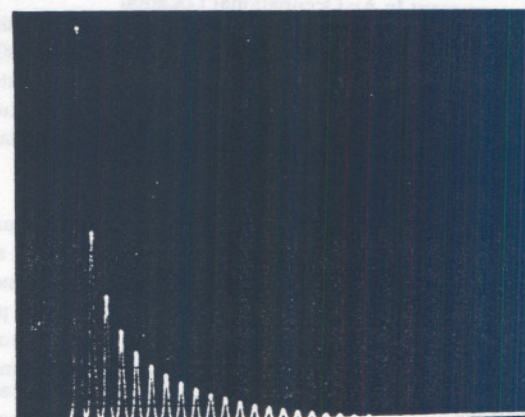


FIGURE 7. Normalized spectrum analyzer display for waveform in Figure 6. Horizontal scale = 200 Hz/div .

3.3 Personal Exposure Meter Measurements: A 24-Hour History

While personal exposure meters can measure the temporal variation of the magnetic field at a single location (see Section 3.4) up to several days, perhaps the most important function of this kind of instrumentation is its capability to record the magnetic field values experienced by a person as a function of time as the person goes about his or her daily activities. Figure 8 shows the magnetic field exposure values, recorded every 7 seconds, of a 10 year old school girl for a period of approximately 24 hours [29]. The data show magnetic field values (vector sum of three spatial components; Section 2.1) experienced by the girl beginning in the afternoon of one day through the following afternoon. While the major sources of the magnetic field are readily identified at certain times (i.e., hair dryer and electric blanket), further measurements, with possibly different instrumenta-

tion (e.g., a survey meter), could be used to determine the sources at other times. Additional measurements would also be required to determine how typical the exposure pattern in the figure was for this person. The data in Figure 8 should not be interpreted as being representative of any group of persons. Although not indicated in Figure 8, the instrumentation is also capable of indicating what percentage of the time (hr) or the time-integrated field (mG-hr) is spent above or below a certain value. Determination of the harmonic content in the fields would require further measurements with different, less portable instrumentation.

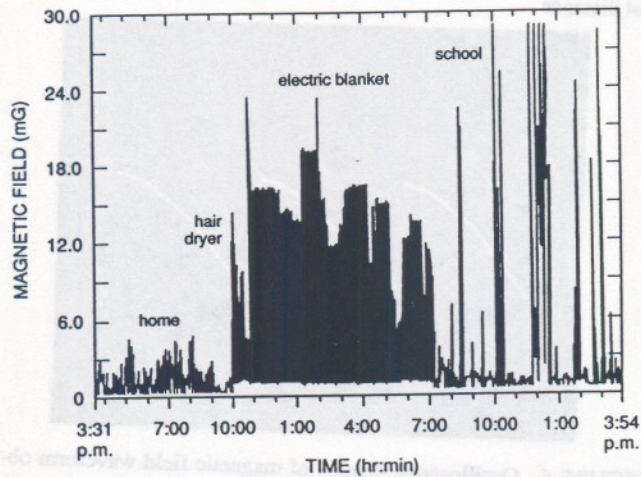


FIGURE 8. Twenty-four hour magnetic field exposure history for 10-year old girl. Data obtained with personal exposure meter.

3.4 Measurement In An Occupational Location

The setting chosen for the last measurement example is the Bonneville Power Administration's Ross 230-kV Substation [30]. The measurements were performed in the vicinity of a fairly isolated 230-kV three phase bus. The phases of the bus are made of solid aluminum tubes that are spaced about 10 feet apart in a horizontal plane approximately 20 feet above the ground.

If a spot measurement were made of the magnetic field under the center phase (near ground level) in the mid-afternoon with a survey meter, the flux density would be near 260 mG at the time of the measurements. How representative this field value is over a period of approximately one day is shown in Figure 9. Figure 9 shows data obtained with a commercially available personal exposure meter that recorded the field value every 10 seconds at the same location for nearly 24 hours. The field (vector sum of three spatial components) is seen to vary by as much as $\pm 21\%$, and after nearly 24 hours, the field is still 15% higher than the previous day.

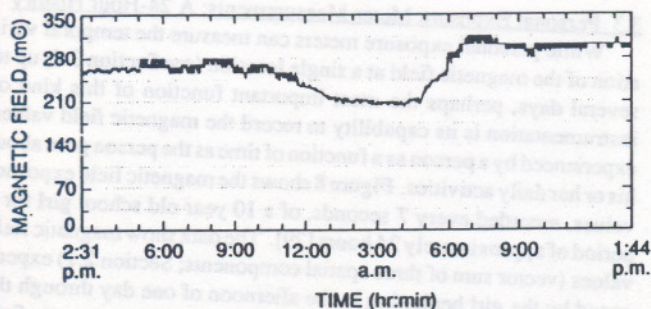


FIGURE 9. Temporal variation of magnetic field measured beneath center phase of 230-kV three phase bus.

One option to characterize the spatial variation of the magnetic field is to measure the lateral profile that passes through the point where the temporal measurements were made. The results of such a measurement, using the exposure meter, are shown in Figure 10. RMS values of the three spatial components as well as their vector sum measured during the early afternoon are indicated. The acquisition of the data was expedited by mounting the exposure meter on a "measurement wheel" which provides a signal indicating location as the wheel rotates along the path of the lateral profile. This signal is fed into the memory of the exposure meter and correlated with the field value at each location.

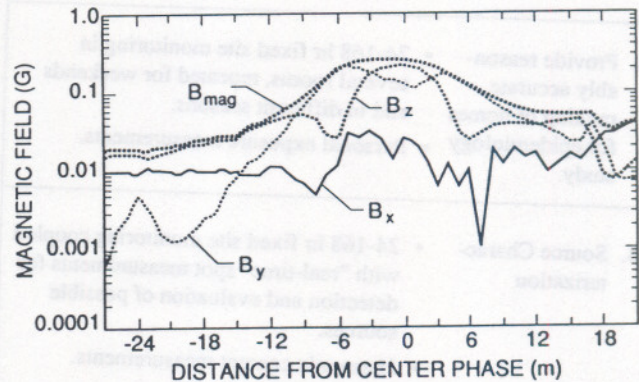


FIGURE 10. Lateral profile of magnetic field components and vector sum near 230-kV three phase bus.

More measurements would be required to determine how representative the one-day measurements are of longer time periods. Further, if knowledge of the harmonic content in the field is of interest, different instrumentation with additional measurements would be required.

4. CONCLUSIONS

The following conclusions can be drawn from the information presented in this paper entitled "Measurements of Power Frequency Magnetic Fields Away from Power Lines":

- instrumentation which can determine the magnitude, temporal variation, and harmonic content of magnetic fields is available for characterizing fields in residential and occupational settings. The number and types of measurements will increase as the measurement goals become more comprehensive.
- miniaturized exposure meters that permit the recording of personal exposure to ambient level magnetic fields during the course of daily activities have been developed and provide for more realistic exposure estimates. The same instrumentation can also be used for measuring the temporal variation of the field at a given location.
- procedures for instrument calibration exist over the dynamic range of interest, i.e., 0.1×10^{-7} T to greater than 1×10^{-4} T (0.1 mG to 1 G).
- outlines of measurement strategies were presented for characterizing residential magnetic fields. These strategies depend on the goals of the measurement program. In the absence of established measurement protocols, the outlined strategies (from Table I) provide some guidance for measurements in residential settings.

information provided in this paper complements that presented in an earlier paper of the AC Fields Working Group, "Magnetic Fields From Electric Power Lines — Theory and Comparison to Measurements" [31].

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L. A. Rosen, Ph.D. (National Institutes of Health, Bethesda, MD): This paper is a major advance in considerations of the characterization of electromagnetic fields, with the recognition that something other than time averaged fields is important. The following comments on the paper are offered more as considerations for how the collected data would be used when collecting data, than as suggestion for changes in the recommendations of measurements.

Table 1 recommends that course measurements be collected as part of Goal 1, "Course ranking of homes for epidemiology studies," but suggests that harmonic characteristics need not be addressed until Goal 3, "Source Characterization," a level of complexity and physical measurements that may not be reached in most epidemiological studies due to funding restrictions. In addition, the paper does not specify whether the residential measurements outlined for Goal 1 include filtering for the 60 Hz fundamental or whether the magnitude of the measurements would include the contribution of a broader range of the power frequency harmonics.

Since the objective of many field characterization programs is to form the basis for establishing exposure for correlation to biological events, the course measurements proposed in Goal 1 could be extended with minimal effort to provide significantly more information. It would appear beneficial to recommend that "course measurements," could include one measurement that is filtered to the fundamental 60 Hz and a second measurement that includes linear or flat range considerations. The recently developed Star Logger, equipped with an adapter (available from EPRI/HVTRC) can independently measure the filtered 60 Hz magnetic field and the total magnetic field minus the 60 Hz component. Other survey meters, such as the Leeper Meter can provide a relative, but usable numerical, value for the difference between flat and linear measurements, representing the harmonic contribution (Kaune et al, 1987). The dual measurements would be taken at all locations suggested in the paper. With this dual measurement, the epidemiologist could have several different factors, including total field, relative contribution of the non-fundamental harmonics and any combination, in addition to the fundamental frequency component for comparing exposure to the occurrence of biological endpoints. The total magnetic field, in addition to a filtered 60 Hz component, could be an important exposure assessment factor, because of the potential coupling of the higher frequencies with the subjects in the defined exposure areas.

Second, the approach represented in Figure 5 of graphing cumulative time as a function of field intensity represents an excellent recommendation for the advance of exposure considerations. However the proposed method would not discriminate between different conditions that would produce the same results. For instance, time above or below a fixed field point could represent a single major shift in power use in a neighborhood while all else remains stable; for a second location, the cumulative values could represent a series of excursions, such as would occur with power use in a house, particularly where appliances cycle repeatedly. In both cases the values as represented in Figure 5 would be similar, but the first would effectively represent only a change in continuous exposure, while the second would represent intermittent exposure. If a sufficient number of measurements were available in the data collection, as indicated in Figure 8, the suggested format could be modified to indicate the number of times per day the fields went above an arbitrary magnetic field level in addition to calculating the percentage of time below the defined level. It would also be possible to set arbitrary upper and lower points, and calculate the number of times the field intensities went above and below these two levels. Depending on the computer capabilities of the scientists, engineers, or epidemiologists, such arbitrary points could be floating during the data analysis stage, and the calculations of frequency of pathological events recalculated with each defined threshold that can be outlined by the biologists or the epidemiologists. The accuracy of this type of calculation would depend on the discrimination of the recording instrument. It might also be possible to outline the different rates of data collection and the trade-offs in recording time and data discrimination.

In that this paper is recommending factors important in the characterization of electromagnetic fields, interpretation of the degree of intermittency could be an important consideration to those concerned with health effects in this field of study who may not be knowledgeable in the developing laboratory science. The instrumentation and the statistical methodologies are available. Relative change in amplitude over time, in addition to, or possibly in lieu of, fixed single thresholds of field intensity could become factors in defining the reasons for difficulties in agreement between epidemiological reports or explaining discrepancies in the laboratory findings.

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The authors are to be congratulated on their thorough discussion of magnetic fields in residential and occupational settings, and of the presently used approaches to the measurement of magnetic fields in these situations. Of particular value is the presentation of major differences with respect to the vicinity of transmission lines.

This discussor would like to draw attention to two further aspects that may be of significance in connection with epidemiological studies, and to solicit comments from the authors.

In addition to the harmonic content of the magnetic field which has been excellently presented in the paper, two further questions of significance to biological studies should also be queried. The first concerns the orientation of the magnetic field, i.e. location of its major axis with respect to the geometry of the subject and the second concerns the decision whether the peak value of the magnetic field or its RMS value is of importance. Both these questions have medical implications and it is definitely presumptuous of us engineers to attempt to answer them. Nevertheless, it is our duty to draw these two aspects to the attention of medical personnel during their evaluation of epidemiological studies and of other medical experiments. It is necessary to point out the physical significance of field orientation and the physical difference between the peak value of the field

vector (\vec{B}_{max}) and its "energy content", $B_{max}(RMS)$.

$$B_{max}(RMS) = \sqrt{B_{max}^2(fund) + \sum_{harm} B_{max}^2(harm)} \quad (1)$$

In contrast the peak value of the magnetic field is

$$\vec{B}_{max} = \vec{B}_{max}(fund) + \sum_{harm} \vec{B}_{max}(harm) \quad (2)$$

Should the phases of individual harmonics coincide unfavourably, there may be very considerable difference between these two quantities. Under that assumption, for the case illustrated in the paper by Figures 6 and 7,

the ratio between \vec{B}_{max} and $B_{max}(RMS)$ is $28.76/12.14=2.37$.

It is the feeling of this discussor that definition (1) may be applicable to processes where heating effects are predominant, while that of equation (2) would be significant to forces-related phenomena.

Finally, as a separate point I would like to raise the long discussed question of threshold levels. While these obviously vary from one individual to another, there must be field levels to which human bodies (or for that matter those of other members of the animal kingdom) have been made immune through the eons of evolution. In my opinion, it would be incorrect to disregard that possibility.

Manuscript received August 13, 1990.

M. MISAKIAN, M. SILVA, AND R. BAISHIKI: The authors thank the Discussors for their interest and discussions of the working group paper. In response to Dr. Janischewskyj's discussion, we agree with his observation that the direction of an ac magnetic field with respect to the subject may be of significance because the magnitude of the induced electric field and associated current depend, in part,

on the cross sectional area (of the subject) that is normal to the direction of the magnetic field direction. Whether the direction of the ac magnetic field should be determined during the characterization of magnetic fields in residential or occupational settings is not clear. Because the magnetic field may be rotating, determining the "direction" (e.g., possibly the semi-major axis of the field ellipse) might be considered excessively time consuming during an epidemiological study when many measurements must be performed. Some members of the bioeffects community have considered the possible influence of the ac magnetic field direction on the outcome of biological studies [1,2].

We agree that it is worth noting that the relationship between peak and rms values for the possibly complex waveforms encountered during measurements of the fields away from power lines may not be as simple as in the case of sinusoidal waveforms. We should also note that the ratio of peak to rms field values in Figure 6 is about 1.76 and not 2.37. This can be determined directly from Figure 6 and the information in the caption. The peak value is near $0.3 \mu\text{T}$ and the rms value is $0.17 \mu\text{T}$. This result can also be confirmed by modeling the approximately sawtooth waveform with the function $f(x)=x$ in the interval $-\pi$ to π . The ratio of $f(x)_{\text{peak}}$ to $f(x)_{\text{rms}}$ is 1.73, which is in good agreement with the measured ratio.

Questions regarding the possibilities of heat and force related bioeffects, and thresholds for the onset of bioeffects are beyond the expertise of the task force.

In responding to Dr. Rosen's discussion, we note that Dr. Rosen is a biologist who is very familiar with the bioeffects research related

to power frequency electric and magnetic fields. Therefore, his point of obtaining some measure of the harmonic content in the field even during the coarse ranking of homes, could be one of many factors considered during any future discussion of measurement protocols. Similarly, the remarks regarding maintaining of flexibility in the acquired data so that thresholds for effects can be explored merits further discussion. As noted in the text (Section 3.3), exposure meters currently exist which can shed some light on time spent in fields above a certain level. Exposure meters can also provide information regarding intermittency of exposure.

In ending this closure, we note a number of "typos" in the text. The "w" in Eq.(2) should be ω , and the a's and b's in Eqs.(4)-(6) should be α 's and β 's, respectively.

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