Measurement of Magnetic Fields
in the Direct Proximity of Power Line Conductors

A. V. Mamishev, Student Member, IEEE  B. D. Russell, Fellow, IEEE
Department of Electrical Engineering
Texas A&M University
College Station, TX 77843 USA

Abstract - Modeling and managing of power frequency magnetic fields requires verification of theory with actual measurements. Measurements only at ground level are not always sufficient for comprehensive studies. The technique and the results of three-dimensional mapping of the power frequency magnetic fields high above ground level are presented in this paper. Comparative calculations illustrate relevance and approximations of the existing theoretical approach to field modeling. The influence of harmonics on the elliptical rotation of the magnetic field vector is illustrated. The possibility of use of the magnetic fields for the power line proximity detection is discussed.

Keywords: magnetic fields, power lines, proximity detection.

I. INTRODUCTION

Several intense measurement studies of power line electric and magnetic fields have been conducted by different agencies and companies in the United States [1], Canada [2] and other countries. A majority of the recent studies have concentrated on the magnetic fields at ground level. Large databases have been built and statistical analyses of the magnetic fields have been performed. Discrimination of the near and far fields usually assumes measurements at one meter above ground level, directly under the power lines and at the distances of several hundred feet away from the lines. Similar earlier series of measurements have been performed for electric fields [3].

Very few studies were concerned with the fields in the direct vicinity of conductors high above the ground. Distances in the range of several feet from the energized conductors have been addressed while concerned about the absorption of the electromagnetic energy by live-line maintenance workers. Both electric fields [4] and magnetic fields [5] have been studied; however, the measurements have been performed only in a few representative spots, i.e., in the typical locations of the maintenance workers.

A more comprehensive quantitative picture of the magnetic fields in the cross-section of the power lines is important for further studies for several reasons. Recently developed software allows computation of the spatial distribution of the electric and magnetic fields at all points above the power line, including those high above the ground. The verification of the results of calculations with actual measurements is hindered by the fact that no standard exists for performing such measurements. Knowledge of spatial distribution of the fields as opposed to the values in a few representative spots allows improved analysis of the health impact of the fields on live-line workers.

Aside from environmental concerns, the interest in such study has been prompted by the search for the solution to the problem of power line proximity detection. The number of injuries and fatalities due to the contact of crane booms and operators of manlift devices with live power lines accounts for a significant percentage of construction site accidents [6]. Electrocutions are the third leading cause of occupational deaths in the United States. In 1984, for example, electrocutions accounted for 9.5% of all reported occupational deaths [7]. The magnetic field can be a good measure for the detection of the proximity of current carrying conductors.

II. SPECIFICS OF THE TASK

Aside from the fact that the goal of this study is somewhat different from that of other studies (power line proximity detection in addition to health concerns), one of the reasons why the fields in the direct vicinity of the conductors have not been studied extensively is that non-standard procedures and equipment are required for such measurements. The mapping of the field requires taking the measurements in many spots, recording them, and further processing the collected data. EPRI dedicated several projects to the development of techniques for effective field mapping [8]. The developed equipment and protocol are adequate for residential and ground level field

measurements, but is not suitable for measurements high above
the ground, i.e., in the bucket of an electric utility maintenance
truck (bucket truck).

Because of the proximity of the measuring device to
the current-carrying conductors, the distance and relative angle to
each conductor is different. Thus, it is important to account
for the elliptical rotation of the field vector \([9]\), as well as for
the frequency content of the field.

For the measurements with a bucket truck, the ability to
move quickly from one point to another and perform snap-
shots of the fields becomes critical for two reasons. First, the
temporal variations on the conductors of the line will affect
the distribution picture of the fields; consequently, high speed
mapping is required in to minimize this source of distortion.
Second, it is desirable to minimize the time of use of the
bucket truck and its operator. The proposed set-up is not the
only one possible, but it proved to be the most efficient among
the methods of fast mapping explored during this study.

III. PROGRAM OF MEASUREMENTS

A. Standard Measurements

The most common type of magnetic field measurement, rec-
ommended by IEEE standards \([10]\) is taking a lateral profile
of the field. In this case, the meter is held at one meter above
the ground, for both electric and magnetic fields. The mea-
asurement is performed across the right-of-way, along the line
perpendicular to the conductors.

In the case of the electric field, a single axis meter is sufficient
for standard measurements. The reason is that the direction of
the electric field near the ground is vertical, as the earth is
almost a perfect conductor in comparison with the air.

The standard technique for the measurement of magnetic
fields depends on whether one wants to measure the maximum
or resultant field. In case of the maximum field, the single axis
meter is aligned along the major axis of the ellipse. For the
resultant field, a three-axis meter can be used, and the separate
sinusoidal signals should be processed appropriately in order
to find the resultant field. In fact, for the single frequency
fields, the sum of the of the rms values from each axis is equal
to the rms value of the resultant field:

\[
B = \sqrt{B_x^2 + B_y^2 + B_z^2}.
\]  (1)

This approach, however, requires separate consideration when
the fields of the higher harmonics are also detected by the
sensor.

B. Performed Measurements

The central group of measurements was the mapping of the
field in the plane perpendicular to the power line, both below
and above the wires, as it is shown on Fig. 1. This series
of measurements will be referred to as an "orthogonal plane"
mapping. Such mapping has not been done previously and is
important to the problem of proximity detection. The space
gradient of the measurand chosen for the detection will define
the reliability of the detection technique.

In addition to the orthogonal plane mapping, several other
studies, such as lateral, longitudinal, and vertical profiles, have
been measured. The purpose of them was to confirm the cor-
correct performance of the system, to minimize the influence of
temporal variations, and to reduce the number of points to
be taken for the orthogonal plane mapping. These additional
measurements are not discussed here as similar studies have
already been reported by other investigators.

Several approaches can be taken in order to locate the meter
high above the ground and orient it in space. Out of six degrees
of freedom (three linear and three rotational), five had to be re-
stricted for the measurements (two linear and three rotational).
This would allow recording of the resultant value of the field
with a high degree of accuracy. Since the resultant value is of
interest, single axis meters would not be adequate.

In general, some of the standard procedures of measurement
could have been used, but significant modification of them was
necessary.

IV. DESCRIPTION OF MEASUREMENT SYSTEM

A. Goals

Since non-standard procedures were to be followed, the mea-
surement system had to be built to meet the specific require-
ments of the task. Overall emphasis on the magnetic field
sensing versus electric field sensing is determined by the fact
that electric field is strongly affected by surrounding objects.
It is almost meaningless to map the electric field distorted by
the presence of the bucket truck, the boom, and the operator it-
self. The relative location of these objects and the meter would
affect the results more then the relative location of the power
line and the meter.
B. Measurement Set-Up

A schematic view of the measurement set-up is shown on Fig. 2. A three-axial magnetic field meter has been built from available single-axis sensing coils produced by the EFM corporation. A low-frequency cut-off filter is necessary in order to eliminate oscillations below 40 Hz caused by the movement of the sensor in the dc magnetic field of the Earth. Since the magnetic field of the Earth varies from 250 milligauss (mG) on the equator to 500 mG on the poles, the voltage induced in the moving sensing coil may significantly exceed measured fields, which are normally in the range of several mG (unless one approaches very close to the wires). The multichannel amplifier with amplification ranges 1-10-100-1000 is necessary not only to bring the signal to a level unaffected by floating charges, but also to provide a means for measuring fields in the close proximity of the conductors and on the ground using the same system. The three-axial sensor and the sensitive circuits of the amplifier, after being built, have been shielded from noise signals by enclosing them in aluminum cases. Shielded cables connected the output of the amplifier with the input of a multichannel instrumentation recorder.

The data has been recorded on a standard high bandwidth multichannel analog tape recorder. After that, the tapes were replayed in the laboratory on the same recorder. The output from the recorder was connected to an A/D converter and the digitized data has been processed using the Global Lab data acquisition software and Windows environment.

This generic set-up has been used for the orthogonal plane mapping. Similar set-ups were used for measurements on the ground. In some cases, recording and waveform capture was not necessary. For these cases, the sensors were connected to a digital voltmeter.

C. Calibration

Calibration of the whole system has been performed in accordance with the requirements of IEEE standards [10]. The magnetic field calibration is normally done by introducing the sensor into a nearly uniform non-polarized magnetic field of known magnitude and direction [11]. A simple square loop with side equal to to 1.5 m of 34 turns of wire has been used. The uniformity of the field has been confirmed by slight changes of the position of the sensor. The rms magnetic field, \( B \), at the center of a square loop with \( N \) turns of wire is given by (2) from [12]:

\[
B = \frac{\mu_0 l N \sqrt{2}}{\pi s} \cdot 10^{-4},
\]

where \( l \) is the rms current in amperes, \( 2 \cdot s \) is the side dimension of the loop in meters, and \( B \) is the value of the magnetic field in Gauss. The field in the center of the horizontal loop is directed vertically. Driving the current of 0.5 A into the loop produces a field equal to 32 milligauss, which lies in the same order of magnitude as the fields to be measured. Due to the capacitive integrator and accurate design of the coil, each of the sensors has a highly linear response.

The ambient temperature during the measurements outdoors has been close to the standard room temperature 20 °C.

V. PROCEDURES

For the orthogonal plane measurement, distribution level 12.5 kV three-phase with ground wire power line has been chosen. No other power lines were located nearby, and the earth surface was flat. A grid of bright orange dots was drawn on the ground along the line perpendicular to the conductors. The distance between these clearly visible fluorescent dots was one meter and the zero point was directly under the central conductor of the power line. The clamp truck was placed next to the line and the measurement assembly was placed into the bucket. All devices were energized from batteries because no wire can be run from the ground to the bucket due to safety requirements. The clamp-on current meters were placed directly on the energized conductors to monitor actual load currents. Within the precision of the clamp-on meters, the load on the line remained the same during the whole process of measurements which took about three hours.

The task of restricting six degrees of freedom of the three-dimensional meter was resolved as follows. While using the plumb drop and watching its thread through a viewing slot in a transparent plastic, the sensor was placed directly above the orange dot on the ground. This provided the \( X \) and \( Y \) coordinates in the horizontal plane (same as the coordinates of the reference dot), and restricted two linear degrees of freedom. The \( Z \) coordinate, height above the ground, was found using an ultrasonic distance measuring tool. The upper limit of
measurement provided by this device was twelve meters which determined the maximal height of measurements. Two compasses, one floating body and the other rotating needle type, were aligned along the line on the ground before the measurements; the compasses guaranteed that the axis of one of the coils was always aligned with the conductors. The readings of compasses are not reliable, however, when the distance to a current carrying conductor is less then one meter, as the power line ac magnetic field becomes comparable to the Earth's dc magnetic field. A three-bubble level ensured the horizontal position of the sensor and, thus, provided a means of restricting two remaining rotational degrees of freedom.

The bucket was moved gradually upward and downward above the grid dots in one meter intervals. After this, the sensor was oriented in space and snap-shot measurements lasting several seconds were recorded on magnetic tapes. An audio track on the magnetic tapes allowed the measurements to be marked with voice.

Separate recording of signals from the three sensors allowed to check alignment of coils and to reject several readings where the orientation of the assembly was lost.

VI. RESULTS

A. Spatial distribution of magnetic field

1) Measurements: The results of the orthogonal plane mapping are shown in the Fig. 3. In this case, the amplitude values of the resultant field determined with 1 were used for the representation. Steep increase of the field as one approaches the conductors is clearly observed.

2) Comparative calculations: The currents in the conductors were monitored during the measurements. Their values remained steady and were equal to 40, 24, and 30 A for the A, B, and C phases correspondingly, and 7 amperes for the neutral N (true rms values). The location of these conductors is shown in Fig. 1. Under the assumption the the angle between the phase currents is approximately equal to 120°, 50% of the return current goes through the neutral, and the rest goes through the ground return path. Using this input data, the spatial distribution of the resultant magnetic field was calculated with MAGFLD program, developed at Washington State University. The results of the calculations are shown in Fig. 4. The values in the closest proximity were cut off in order to picture the distribution of the field in the area of interest. Larger area of the power line cross-section is plotted for the calculations (Fig. 4) than the one for the measurements (Fig. 3) in order to better illustrate trends of the spatial distribution of the magnetic field.

The close correspondence of the patterns of distribution can be clearly observed. The difference between measured and calculated values does not exceed 20 % for most locations. At the locations closest to the conductors, this difference may be much higher, although the values still are of the same order of magnitude. Certain discrepancies in the values of the field are common for such studies. They appear due to several approximating assumptions, such as value of conductivity of earth (100 Ω for a given case), value of the return currents, sag of the wires, temporal variations, harmonics, geometrical distance errors, and others.

3) Proximity detection issues: Geometrical symmetry of this power line allowed to take measurements of only one side of the plane and create a mirror image of it for the whole picture. This approximation would be precise if the currents on the line were exactly balanced. In order to justify the validity of this approach, several sets of measurements were taken for the points symmetrical to the vertical plane containing the poles of the line.

Based on this assumption, the picture of the magnetic field around the power line has been created (Fig. 5). It demonstrates how the magnitude of the resultant magnetic field can be used for alarming of proximity of the bucket truck operator to the power line conductors.

The behavior of the magnetic field at 60 Hz frequency makes it almost ideal for detection - if the currents are present in the line. However, if no load is connected to the line, then the only currents which will flow will be the capacitive currents from the conductors to the ground. For the distribution level lines, these currents are not sufficient to create a magnetic field significantly different from the background fields.
Fig. 5: Proximity belts based on the amplitude of the resultant field.

B. Elliptical polarization of the field vector

Discussion of the measurements and detection so far has been limited to the magnitudes of the measurands. The measurement of the polarization of the fields is another possible solution, or, better, additional technique for proximity detection. Two measurements are given here for the comparison. Fig. 6 visualizes the ellipse traced by the magnetic field vector at the point 4 meters above the ground and 7 meters from the center of the line. Next, Fig. 7 shows the magnetic field ellipse at 1 meter above the ground and 25 meters from the center of the line. It should be noted that the vertical axis of the graph at Fig. 7 has a much smaller range, so the relation of the major axis to the minor axis is even more dramatic than it appears to be. The reason for this change of degree of polarization is obvious. In the second case, the angular difference between the location of the source currents is much smaller than in the first case, because the second point of measurements is much more remote from the line. In the case of Fig. 7, the sinusoidal output of the coils is almost in phase. The signals which form an ellipse on Fig. 6 are shown on Fig. 8. The reason that the ellipses are so distorted becomes obvious after seeing the shapes of the waveforms. The harmonic content is very high. An FFT of one of the signals on Fig. 8 is shown on Fig. 9. Similar frequency spectrum has been observed for most locations.

The content of the higher harmonics and, thus, distortion of the shape of the ellipse, is slightly exaggerated, because the frequency response of the measuring system is non-linear. The true third harmonic content is in fact approximately 1.5 times smaller than shown on the Fig. 9, and other, smaller correcting factors can be applied to the other harmonics. In our case, however, the output of the sensors is intended to be processed for the proximity detection. The restoration of the original waveforms is pointless and will require either additional computation power or design of special filters.

Fig. 6: Two-dimensional rotating vector of the magnetic field, 4 meters above the ground, 7 meters from the center line.

Fig. 7: Two-dimensional rotating vector of the magnetic field, 1 meter above the ground, 25 meters from the center line.

Fig. 8: Waveforms of the single-axis unit response to the rotating magnetic fields vector.
VII. CONCLUSIONS

The results of measurements of the magnetic fields in the direct proximity to the power line conductors are reported here. The measurements are compared against computer calculations, a close correspondence between them has been observed. High harmonic content of the phase currents significantly distorts the distribution picture and the shape of the trajectory of the elliptically rotating vector of the magnetic field. This last issue must be taken into account for certain tasks related to the power frequency magnetic fields.

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IX. REFERENCES


Alexander V. Mamishov was born in the Soviet Union in 1971. He received the B.S. degree from Kiev Polytechnic Institute, Ukraine in 1992. He is presently enrolled in the M.S. program in electrical engineering at Texas A&M University. His fields of interest include electric and magnetic fields, electroacoustics, thermodynamics, and degradation of polymeric insulation. He is a recipient of the IEEE Vincent Bendix Award and the IEEE PES T. Burke Hayes Award. He is an author of about ten technical publications in four countries. He is a student member of IEEE PES, EMC, DEIS, and VTS societies. He is also a member of and Eta Kappa Nu.

B. Don Russell (F '92) received the B.S. and M.E. degrees in Electrical Engineering at Texas A&M University. He holds a Ph.D. from the University of Oklahoma in power system engineering. Dr. Russell is Professor of Electrical Engineering and Executive Associate Dean of College of Engineering at Texas A&M University. His research centers on the use of advanced technologies to solve problems in power system control, protection, and monitoring. He holds several awards and patents for advanced digital technology applications. Dr. Russell is Secretary of IEEE PES. He is a member of the Substation Committee, and chairs several working groups. He chairs annual TAMU Conference for Protective Relay Engineers. He is a Registered Professional Engineer and a member of Texas Society of Professional Engineers.