An E.M. Method for Earth Resistivity Measurements Using Power Line Harmonic Fields

D. C. MCCOLLOR,* T. WATANABE,* W. F. SLAWSON,* and R. M. SHIER**

**Department of Geophysics and Astronomy,
University of British Columbia,
Vancouver, B. C., Canada*

***British Columbia Hydro and Power Authority,
Surrey, B. C., Canada*

(Received August 9, 1982; Revised May 17, 1983)

An experiment was carried out to infer ground conductivity by making use of magnetic fields created by a power line carrying electric currents as source signals for E.M. exploration. The experiment was done in an area, $10\text{ km} \times 10\text{ km}$ approximately, which is under an overwhelming influence of a major 3 phase a. c. power line. It runs generally east-west and south of the area. The magnetic field measurement showed that the 60 Hz, 180 Hz, 300 Hz, and 420 Hz signals were the four strongest harmonic components. A plot of the field measurements along a north-south line, normalized to the value at a reference station, shows that the vertical magnetic field strength decreases inversely with the distance from the power line in the vicinity of the source and to the cubic inverse of the distance further from the source. The crossover distance (between the $1/r$ relation and $1/r^3$ relation) is dependent on frequency. Extension of an existing theory predicts this trend with the crossover distance $\sqrt{2}$ times greater than the skin depth, providing that the Earth is considered a uniform conductor. The effective resistivity is inferred to be of the order of $10^4\ \Omega\text{m}$ from the crossover distance for 300 Hz and 420 Hz. No crossover is seen for 60 Hz, and for 180 Hz, the fall-off $\propto 1/r^3$ begins to take place near the edge of the survey area ($\sim 10\text{ km}$ in distance from the power line). A deviation from the general trend occurs at the same location for all four frequencies. A change in geologic material in the subsurface is mapped in this locality.

1. Introduction

Electromagnetic exploration methods may be divided into two broad categories depending upon whether the exploration source signal is natural or man-made. An example of the first category is AFMAG (WARD, 1959) which as the main source signal uses audio-frequency magnetic fields created by distant lightning discharges. Approaches of the second category are divided into two groups: one generates signals specifically for exploration purposes (the controlled source method) and the other makes use of signals created originally for purposes other than exploration. An example of the first is a long wire method with a current source designed for

exploration (e. g., DUNCAN *et al.*, 1980). Turam method and horizontal-loop method also belong to this group (TELFORD *et al.*, 1976, p. 540). An example of the second is the technique making use of the high power VLF (very low frequency) transmission which is normally used for air and marine navigation (TELFORD *et al.*, 1976, p. 507). In either approach, frequencies other than 60 Hz (or 50 Hz) and its harmonics are used normally, because fields created by currents carried by power lines are presumed to be noise for E.M. exploration. Actually, power line frequencies and harmonics are often rejected in conventional E.M. exploration methods. Not only in E.M. exploration are power harmonic fields a serious noise source but also for observation of natural audio-frequency (AF) radio waves (HAYASHI *et al.*, 1978). In fact, it is very hard to find a site free of noise of 60 Hz and its harmonics in observation of natural AF radio waves. Usually, a separation distance of 10 km is not sufficient to escape noise from a major power line. If power line noise is that strong, however, it can be made use of as source signals for E.M. exploration. The idea may be quite practical in remote regions where only a limited number of power lines affect an area to be surveyed.

This paper presents the results of an experiment to investigate if power harmonic fields can readily be used as source signals for E. M. exploration. A long power line, straight, isolated, and running through a rural area was used. It was found that strength of the magnetic field decreases inversely with distance in the proximity of the power line and diminished in proportion to the inverse of the cube at greater distances. It was also found that local deviations from this general trend correspond to surface features such as lakes and/or glacial deposits.

2. Choice of Site

For this operation, a 500 kV power line, 5L82 of B. C. Hydro, was used as a source device (Fig. 1). The power line is part of a 3-phase 60 Hz system. The conductors forming the three phases of the power line are in a flat configuration, i. e., they are all at the same height above ground. The horizontal spacing between phases is ~ 10 meters. The power line runs between Meridian Substation, Port Moody (near Vancouver) and Nicola, B. C., about 200 km northeast of Vancouver. The magnetic field observation was done in the Research Forest of U. B. C. (abbrev. of Univ. of B. C.) and an adjacent area (see Figs. 1 and 2). The area is about 10 km by 10 km. The power line cuts through the southwestern corner of the whole survey area. It runs generally east-west, although it bends just outside the western edge of the area. There is no significant power line within the survey area, and major power lines other than 5L82 exist at sufficiently great distances.

3. Characteristics of Source Current

Prior to the main experiment carried out at the chosen site, a preliminary investigation was made to look into the characteristics of the source current. The following two quantities were measured at Meridian Substation: Firstly, the current

Fig. 1. Major power lines in Vancouver area. The U. B. C. Research Forest occupies a western half of the survey area. The rest is part of Golden Ears Provincial Park.

in one of the 3 phase conductors (A-phase) and secondly, the neutral current, i. e., the algebraic sum of the currents in the three conductors.

The significance of the neutral current to the present investigation is as follows. The field at a distance from the power line is the sum of the three fields produced by the currents in the three phases of the line. At a location that is far from the power line compared to the phase spacing, the distances to the three phase conductors are almost equal and the three individual fields are therefore almost proportional to current in the three phases. Since the neutral current is the algebraic sum of the three phase currents, the total field is almost proportional to the neutral current.

The system to measure the power line current is schematically presented in Fig. 3 (a). The A-phase current was measured by detecting the voltage output of a current probe attached around a conductor in the secondary circuit of the current transformer that is permanently installed at Meridian Substation to monitor the current in A-phase of 5L82 power line. Voltage output from the current probe was fed into two amplifiers, one a broadband amplifier and the other involving a 60 Hz notch filter to relatively enhance higher harmonics, and their outputs were logged by an AF tape recorder. The neutral current was measured with another probe attached around a conductor carrying the sum of the currents in the secondaries of all three current transformers installed in A-, B-, and C-phases of the 5L82 power line. The amplified voltage output from this probe was logged by the tape recorder simultaneously with the A-phase current data. Time code from a precision clock was also recorded simultaneously.

The measurements of the A-phase current and the neutral current were carried out several times during a period from March to June of 1981. About three hours of

Fig. 2. Simplified geological map of survey area. The measurement points are marked with a cross. Dashed lines AB and CD show the position of the profiles illustrated in Fig. 6 and Fig. 7.

data were obtained in total. Both A-phase and neutral current data were broken down into harmonic components as a function of time. Fig. 4 shows the spectrum of the A-phase current during a time interval of about 40 minutes on March 3, 1981. Fig. 5 presents the neutral current spectrum during the same time interval. Strength of every harmonic component fluctuated during the period. The range of fluctuation is indicated by the length of the line-segment showing the current strength.

Figure 4 shows that 60 Hz in the A-phase current is the predominant component, followed in importance by three higher harmonic components, 180 Hz, 300 Hz, and 420 Hz. These four components are also important in the neutral current (Fig. 5). In the neutral current of a perfectly balanced 3 phase power system, harmonic currents of the positive phase sequence, viz., 60 Hz, 240 Hz, etc., and of the negative phase sequence, viz., 120 Hz, 300 Hz, etc., should vanish completely, whereas current components of the zero phase sequence, viz., 180 Hz, 360 Hz, etc., should be 3 times

Fig. 3. Each current transformer (abbreviated with CT in (a)) has a ratio 400:1. In other words, a 400 Arms current at 60 Hz in one phase of a conductor creates a current of 1 Arms in the secondary winding. The frequency response was assumed to be uniform. Each of the two current detectors was calibrated at Meridian Substation, regarding the current probe-amplifier-tape recorder as a system. Currents of known strength and frequency were fed into the probe and the signals played back from the tape recorder were analyzed with a spectrum analyzer. A whole system calibration of the mobile AF receiver (antenna-preamplifier-tape recorder) was carried out in a laboratory. Magnetic fields of known strength and frequency were applied to the antenna and spectrum analysis of the tape-recorded data was done in a similar manner. All the data, power line current and AF magnetic field, were analyzed with one spectrum analyzer for calibration as well as analysis of the field data. Time information provided by WWV signals is estimated to be about 0.1 second or better in precision. The precision was checked as follows. The internal clock at the base station was synchronized to the WWV tone of the minute signal. The clock generates pulses at every one-tenth second which were displayed on one channel of a pen-writing recorder. Time pulses of WWVB signals (coded electric signals) were displayed simultaneously on a second channel of the pen-writing recorder. The clock pulses and WWVB pulses never departed from one another by more than 0.1 second.

Fig. 5. Spectrum of neutral current, observed at the same location and during the same time interval as for Fig. 4.

Fig. 4. Spectrum of A-phase current, observed at Meridian Substation, 21h40m–22h20m U. T., March 3, 1981.

greater than those in a single phase (BLUME *et al.*, 1938). Comparison of Figs. 4 and 5 reveals that at 60 Hz the neutral current is smaller than the A-phase current by a factor of about 20 and also at 300 Hz and 420 Hz by a factor a little less than 2. Existence of these three harmonic components in the neutral current indicates that the power system is not perfectly balanced. The 3rd harmonic component (180 Hz) in the neutral current is about 2.5 times greater than that of the A-phase current, i. e., the enhancement factor is less than 3, the value for a perfectly balanced power system.

Spectral analysis was carried out for all the data obtained. The spectra from other time intervals are almost identical to those shown in Figs. 4 and 5. The 60 Hz, 180 Hz, 300 Hz and 420 Hz are the important and stable components. The other components are smaller except for second harmonic (120 Hz) in the neutral current. Its strength fluctuates but is generally stronger than that in the A-phase current. It is comparable with the 5th component (300 Hz) in the neutral current for the time interval represented by Fig. 4. Why the second harmonic is strong in the neutral current remains unknown.

The three higher frequency components, 180 Hz, 300 Hz and 420 Hz, of the four components mentioned previously, are all odd harmonics, i.e., 3rd, 5th and 7th. This indicates that they are generated by symmetric non-linear (symmetric *B-H* hysteresis) devices such as transformers or by three-phase connections of rectifying devices such as diodes and thyristors.

4. Field Operation

The area chosen for this experiment is rugged and of limited accessibility. Coverage of the area was carried out with a mobile receiver—a truck with a set of instruments. Continuous measurement of the magnetic field was made at a base station while the field coverage was in progress. The base station was about 350 meters from the power line. Only the vertical component was measured at both mobile and base stations. The continuous observation at the base station enabled us to monitor fluctuations in the source magnetic field due to variations of the power line current.

The magnetic field measurement systems at the base station and mobile station are schematically represented in Fig. 3 (b) and (c), respectively. Magnetic field measurement was made with an AF radio receiver. The receivers used at the mobile station and the base station are identical. The receiver, which is light and portable, consists of a loop antenna and a preamplifier. The preamplifier is battery operational.

At the mobile stations, output from the preamplifier was fed into a cassette tape recorder. This is also battery operational and has two recording channels. WWV time information was recorded on the second channel. The cassette tape recorder has a built-in amplifier whose gain is variable. Three different gain settings were used depending on signal strength. On the other hand, the preamplifier was used at a fixed gain. Calibration of the AF receiver system, i. e., antenna-preamplifier-recorder as a whole, revealed that the sensitivity is proportional to frequency in a range of interest to us (50 Hz to 1 kHz) within a precision of approximately $\pm 5\%$. This error is due to

limited capacity of the cassette tape recorder in reproducing signals. The sensitivity with the highest gain setting is $1 \text{ mV r. m. s./nT} \cdot \text{Hz}$. For example, a magnetic field of 1 nT r. m. s. at a frequency of 100 Hz gives rise to a voltage of $0.1 \text{ volt r. m. s.}$ The relative sensitivities of the two lower settings are -10 dB and -23 dB , compared with the highest gain setting.

At the base station, output from the preamplifier was recorded with a 4-channel laboratory type tape recorder which requires a $60 \text{ Hz}/115 \text{ V}$ supply. This instrument has four recording channels of which three were used. The output from the preamplifier was recorded in one channel with constant gain setting. Time information was recorded in two other channels, one for WWV signals and the other for time codes from a precision clock.

The AF receiver at the base station was calibrated relative to that of the mobile receiver. The two receivers were run simultaneously. No specifically designed calibration signal was applied. Inputs to both receivers were from power line 5L82. The spectra of the records by the two receivers were compared. Thus, readings from the two receivers can be converted to one another.

The antenna was placed at least 10 meters from the truck during magnetic field measurements at each mobile receiver station. The preamplifier was placed beside the antenna. The cassette tape recorder was put about 5 meters from the antenna/amplifier. At the base station, the antenna/preamplifier was placed about 100 meters away from an electronics hut in which the 4-channel tape recorder was located. Output from the preamplifier was fed to the tape recorder with a 2-conductor shielded cable. Commercial power, 115 volt A. C. was available at the hut. The total power consumption was about 300 watts.

Preliminary magnetic field measurements were made in the summer of 1979 and 1980,¹ once during each year. The main field operation reported in this paper was carried out on July 22nd and 23rd, 1981. The same antenna/preamplifier system was used for all these operations. The 1979 and 1980 operations were carried out in the U. B. C. Research Forest at nine and thirteen points, respectively, covering a distance from the power line up to 8 and 10 km. These preliminary surveys confirmed that the power line current creates a magnetic field strong enough to be detected by the antenna/preamplifier system. During the main operation, measurements were made at 66 points, including all the points covered by the preliminary surveys, and the base station.

5. Magnetic Field Data, Results of Analysis and Discussion

The magnetic field data obtained during the main operation (1981) were processed as follows. First, the data were treated with a spectrum analyzer. The analyzer is an analog/digital hybrid instrument. It reads in analog data and displays a

¹Watanabe, T., Slawson, W. F., and Chapel, B., (1981). "Power Harmonic Radiation as an E. M. Prospecting Source", U. B. C. Dept. of Geophysics and Astronomy (Aeronomy Group) Internal Report, 1981.

spectrum in both digital and analog form. The analyzer was set up to produce an average of 64 consecutive spectrums from a data block of a duration of 18 seconds. Through these spectrum analyses, it became clear that 60 Hz, 180 Hz, 300 Hz, and 420 Hz are the most important and stable as in the case of the source current. The second harmonic was smaller than these four and was less stable. Strength of each of these four important components was read out from every averaged spectrum. The reading at the mobile station was normalized to the value of the base station at the same time. The normalized value is subject to an error estimated to be $\pm 10\%$, because measurements at both mobile and base stations are subject to errors of $\pm 5\%$. The effects of the time-changes in the source current strength were removed by this process of normalization. The errors due to inaccuracies in timing at mobile and base stations are negligible. Precision in timing was about 0.1 seconds at each station, much shorter than the 18 second averaging time. The power line source current was found to be very stable. It changes with a time scale of several hours, much longer than the averaging time. Exceptions were sudden step changes in the source current strength. However, they are very easy to point out, monitoring the base station signals.

The data processed in the manner described in the previous paragraph are presented in Figs. 6 and 7. The figures show the magnetic field strength as a function of distance on the profiles AB and CD (Fig. 2). The stations used in the profile data were within ± 500 m of the lines AB and CD shown in Fig. 2. Exceptions include the base station for profile AB and the three southernmost stations (including the base station) for profile CD. There are four diagrams in each of the Figs. 6 and 7, corresponding to the four important harmonic components. In Fig. 6, we see that near the power line the magnetic field strength of each component varies in proportion to the inverse of distance. Every diagram is a log-log plot and the data points fall on a straight line, 45° downward to the right. Away from the power line, however, the data points systematically deviate from the line of 45° . The trend is clear for the 5th harmonic (300 Hz) and 7th harmonic (420 Hz) at distances greater than about 6 km. In actuality, the field strength there varies in proportion to the inverse of the cube of distance. The change in dependence of the field strength with distance is seen in Fig. 7 also. The change is clear for the 3rd, 5th, and 7th harmonics.

The above-mentioned change in the field's dependence with distance agrees with a mathematical theory developed by PRICE (1950) and also by WAIT (1962). The theory analyzes the electromagnetic field induced in a model earth (a flat earth with a uniform conductivity) by an infinitely long line of A. C. current. The line current is assumed to flow outside the earth and parallel to its surface at a height of, say, h . The theory shows that the induced field is negligible in the vicinity of the power line. Consequently, the field in that region is equal to the source magnetic field, i. e., the field directly due to the current. If the current is expressed as follows (rationalized M. K. S. units are used throughout this section):

$$I = I_0 \cos \omega t, \quad (1)$$

Fig. 6. Profile of field strength along AB. Ordinate represents vertical magnetic field intensity normalized to base station value and abscissa distance from power line 5L82 measured along line AB.

Fig. 7. Profile of field strength along CD. Meanings of ordinate and abscissa are similar to those in Fig. 6.

the vertical component of the direct magnetic field on the earth's surface at a distance r from the power line is expressed as follows:

$$B_z = 2 \times 10^{-7} \frac{I_0}{r} \cos \omega t. \quad (2)$$

To be more precise, r is not the distance from the power line but the distance between the field point and the projection of the line current on the earth's surface. In the above equation, it is assumed that $r \gg h$. Under the same assumption, the theory leads us to the following expression which holds at distances far from the power line:

$$B_z = 4 \times 10^{-7} \frac{p^2 I_0}{r^3} \sin \omega t. \quad (3)$$

In this equation, p is the skin depth of the earth conductor which is given by the following equation,

$$p = \sqrt{\frac{2}{\mu \sigma \omega}}. \quad (4)$$

In this equation, μ and σ represent the permeability and conductivity, respectively. Equation (3) shows that B_z varies in proportion to the inverse of the cube of the distance, r . The derivation of the equations (2) and (3) from the theory are explained in the Appendix.

In applying the theory to our data, it is assumed that the source current is not the actual three phase power line current but the neutral current flowing in a single conductor. This assumption is justifiable, because every station is located at a distance far from the power line compared with the phase spacing. The phase spacing is 10 meters, whereas the distance between the power line and the base station, the nearest station from the power line, is 350 meters. The errors brought by the assumption to the source magnetic field (vertical component) at the base station, are estimated to be not more than the following values; 2% for the 60 Hz component, 0.2% for the 300 Hz and 420 Hz components, and 0.1% for the 180 Hz component.

The source magnetic field (2) becomes equal to the asymptotic field (3) at the following distance, r_c :

$$r_c = \sqrt{2} p. \quad (5)$$

This gives the crossover distance where the magnetic field variation changes from the $1/r$ dependence to the $1/r^3$ dependence. Figure 8 shows exactly how B_z changes over a span of distance covering the crossover region. The abscissa in this figure represents the distance r measured in units of the skin depth, p and the ordinate the magnetic field B_z in units of B_c . B_c is the value of B_z (from equation (2) or (3)) for which $r = r_c$.

$$B_c = \sqrt{2} \times 10^{-7} \frac{I_0}{p}. \quad (6)$$

Fig. 8. Theoretical profile of field strength. Abscissa represents distance in units of skin depth. Ordinate means magnetic field in units of B_c , defined with the Eq. (6). The two asymptotes to the profile, $1/r$ and $1/r^3$, intersect at the distance r_c which is $\sqrt{2}$ times greater than skin depth. B_c is the field strength at this distance. The profile is based on Table 1 and Fig. 2 of Price's paper (1950), for the case that height of the power line is zero, i. e., $h = 0$ and consequently $\zeta = 0$. The profile is virtually independent of h according to our computation.

With the crossover distance determined from the intersection of the asymptotes, one can find the skin depth and resistivity, using the equations (5) and (4). Those two equations yield the following formula,

$$\sigma = \frac{0.5066}{fr_c'^2}. \quad (7)$$

where r_c' is the crossover distance in km and f the frequency in Hz. The permeability μ is assumed to be equal to $4\pi \times 10^{-7}$ henry/meter. The conductivity σ is in units of Mho/meter. The inverse of σ gives the apparent resistivity ρ_a in Ωm :

$$\rho_a = 1.974fr_c'^2. \quad (8)$$

The resistivity or conductivity determined through the procedure described above is only an apparent one for each specific frequency. The equations which the formulae (7) and (8) are based on are subject to the assumption that the earth be a uniform conductor.

The crossover distance and the apparent resistivity obtained from the field data are listed in Table 1. The crossover distance in this table is measured from the power

Table 1 Resistivity inferred from crossover distance.

Profile	Harmonic frequency (Hz)	Crossover distance (km)	Resistivity (Ωm)
AB	300	5.5	1.8
	420	5.9	2.9
CD	180	3.0	3.2
	300	3.0	5.5
	420	2.3	4.3

line. In other words, it is the length of the perpendicular from the crossover point to the power line. There are two sources of errors in the estimate of every crossover distance. One is due to the errors of the data points in Figs. 6 and 7. Every data point is subject to an error of $\pm 10\%$ which will bring in an error of about $\pm 20\%$ in determining the crossover distance, r_c . This degree of uncertainty in r_c yields an error of about $\pm 40\%$ to an estimate of the apparent resistivity. Another error source is the ambiguity in direction of the power line. The formulae (7) and (8) are based on an assumption that the power line is straight. In view of the map of Fig. 1, the power line was modelled with an infinitely long straight line as indicated by 'BASELINE' in Fig. 9. In actuality, however, the power line is bent about 5 km west of the profile AB. How much the source magnetic fields due to the actual power line current and to the model current are different from each is shown in Fig. 9 also. A contour labelled with 20, for example, means that the vertical component of the actual source field is 20% (1.2 times) stronger than that of the model source field. The actual source magnetic field was calculated by applying the Biot-Savart law to that segment of the 5L82 power line from the Meridian Substation to the eastern limit of Fig. 1. Both actual and model source fields are assumed to be unity in strength at the base station. Of course, no current induced in the ground was taken into account for calculation of the source field. On the profile AB, the difference between the actual source field and the model one is not more than 15%, and on profile CD, it is about 5% or less. An improvement in data analysis, taking the power line bending into account, can be made by approximating the source current with a series of line-current segments or electric dipoles along the 5L82 power line.

Despite the error sources mentioned in the previous paragraph, it may be safe to say that the resistivity is in a range from $10^3 \Omega\text{m}$ to $10^5 \Omega\text{m}$. Resistivity of most igneous and metamorphic rock falls in a range from $10^2 \Omega\text{m}$ to $10^8 \Omega\text{m}$ (TELFORD *et al.*, 1976, p. 454).

It is worthwhile to note that the apparent resistivity calculated from the field data is different from frequency to frequency. This indicates how resistivity varies with depth. If the estimated apparent resistivities happen to be free of the errors mentioned above, the greater resistivity for 420 Hz on the AB profile compared with that for

Fig. 9. Difference between the model source field and the actual source field.

300 Hz would indicate that resistivity is lower at a greater depth. The dependence of the apparent resistivity on frequency on the CD profile might indicate a three layer structure in which the middle layer is most resistive. The electromagnetic field induced in an arbitrary number of layers by an A. C. line source has been mathematically analyzed by WAIT (1962). The analytical solution worked out by Wait will be useful in finding a layered structure model which fits the observational data best (a least squares fit, for example).

The effective resistivities on the AB profile are systematically greater than those on the CD profile. With regard to this resistivity contrast, it is interesting that a geological fault has been mapped as existing between the two profiles (see Fig. 2). The resistivities of the two regions divided by the fault may be different from one another. Actually, surface geological features are different between the two regions. A geological map shows that an area of glacial deposits spreading south of the survey area protrudes in a form of a narrow strip up to Alouette Lake along the profile CD. On the other hand, the area represented by the profile AB is mostly underlain by rocks such as quartz diorite and diorite. A strip of glacial deposits runs along the profile AB from the northern end of the survey area to a few kms. south of Jacobs Lake. However, this strip of glacial deposits is narrower and presumably shallower than that along the profile CD. Also, it is not connected with the wide open glacial

deposit area south of the survey area, unlike the glacial deposit along the profile CD.

The magnetic field vs. distance profile for 420 Hz on the CD profile indicates that there are two crossover points. No such double structure is seen in the profiles for 180 Hz and 300 Hz. It should be noted, however, that for each frequency, the region of the $1/r^3$ dependence is followed with a second region of $1/r$ dependence. Whether the dependence is precisely proportional to $1/r$ or not in the second region should be investigated with more data. The authors also refer to the second region of $1/r^3$ dependence with some reservation. The meaning of the double structure in profile remains unresolved. However, it may be that the conductivity changes laterally at the boundary between the first region of $1/r^3$ trend and the second region of $1/r$ dependence. It is interesting that the region of the second $1/r$ and/or $1/r^3$ dependence corresponds to the Alouette Lake glacial deposit region. Conductivity of surface water, which is generally higher than that of base rocks, may be responsible for these results.

In Fig. 6, a deviation from the general trend of $1/r$ to $1/r^3$ exists in a range of distance from 4 km to 6 km, for every harmonic. A small lake (Jacobs Lake) exists within a glacial deposit in this region of anomaly. For 420 Hz, the deviation starts at a shorter distance, about 2 km. This might indicate that there is a region of better conductivity at a shallower depth to the south of the lake region. In Fig. 7, a deviation from the general trend exists at a distance of a little less than 2 km. The anomaly exists for all harmonic components. However, it is more pronounced for 300 Hz. It might indicate the existence of a small body of a higher conductivity, at a depth optimal for detection by 300 Hz. However, it should be noted that the two data points out of the three in this region of anomaly are off the profile CD by 1.3 km and 0.8 km, respectively.

6. Conclusions and Recommendations for Future Research

The main results obtained through this investigation are as follows.

(i) Strength of the vertical component of the magnetic field created by a current in a long straight power line varies inversely with the distance from the power line in the vicinity of the source and at sufficiently great distances, inversely with the cube of the distance.

(ii) The crossover distance where the general trend changes from the $1/r$ dependence to the $1/r^3$ dependence falls in a range from 2 km to 6 km, approximately. It depends on frequency and differs from one region to another. In case of a homogenous conducting earth, the crossover distance is $\sqrt{2}$ times greater than the skin depth. A straightforward application of this theoretical result shows that the apparent resistivity is of the order of $10^4 \Omega\text{m}$ in one region and $5 \times 10^3 \Omega\text{m}$ in another.

(iii) A few deviations from the general trend, the $1/r$ to $1/r^3$ dependence, were found. Location of every deviation is independent of frequency, though its size depends on frequency. In one case, the deviation corresponds to the location of a small lake within glacial deposits. It seems that these deviations can be considered as anomalies in the sense of E.M. exploration.

These results show that magnetic fields created by power-line carried currents can really be used for E. M. exploration. This approach will be referred to as the PHM (power harmonic magnetic) method hereafter in this paper. It is essentially a long wire E.M. method. However, currents in this method are usually supplied from a controlled source avoiding 60 Hz (or 50 Hz) and its harmonics. Besides, a long wire has to be set up in a conventional method except in a lucky situation such that an unused power line is available. An advantage of the PHM method is that one can save trouble setting up a current source and a long wire. A disadvantage of the PHM method is that data analysis would generally be complicated compared with the controlled source techniques. The PHM method will not replace the other well-developed E.M. exploration methods but may complement them. The controlled source methods may not work in regions where fields of power-line sources are overwhelmingly strong. In such regions, there may be no practical way other than using power harmonic fields as source signals. R. E. Niblett¹ informed the present authors of an investigation which is particularly interesting in this respect. The investigation was done by Strangway *et al.*² They used electromagnetic fields created by a power line current for an AMT (audio-frequency magneto-telluric) survey. Their technique may be referred to as the PHMT (power harmonic magneto-telluric) method. The survey work was done in Chalk River, Ontario, covering an area of about 1 km $\times$ 1 km. Four different frequencies were used: 60 Hz, 180 Hz, 300 Hz, and 660 Hz, which in their case was apparently stronger than 420 Hz. The AMT method, or the magneto-telluric (MT) method in general, normally uses a pair of horizontal and mutually orthogonal magnetic and electric fields of a natural origin. Strangway *et al.* found that natural E.M. signals were contaminated so much by power-line sources that a conventional AMT survey was not considered worthwhile to complete. They rather used power-line source fields at 60 Hz and its three main harmonics. The apparent resistivity was calculated for each frequency. The results indicate several linear features of an anomalously low resistivity. In one of such features, the width is less than 100 m and the variation in resistivity is close to an order of magnitude.

The PHM method can be improved through further investigation. The method of data interpretation presented in this paper is based upon a crude model of the Earth—a flat earth of a uniform conductivity. E.M. fields induced in a model earth of a layered structure have to be analyzed so that we can prepare a sufficient number of type curves. Whether an inversion technique can be applied to the PHM method or not is worthwhile studying. Structures involving lateral resistivity changes are harder to analyze. Modelling will be helpful for such cases.

It will be helpful if the magnetic field due to currents induced in the ground can be separated from the inducing field. The induced field should bear effects of con-

¹ A personal communication, 1982.

² Strangway, D. W., Redman, J. D., Holladay, S. and Horne, C. (1980). "Audio-Frequency Magneto-Telluric Soundings at the Whiteshell Nuclear Research Establishment and Chalk River Nuclear Laboratories", for Atomic Energy of Canada Limited.

ductivity anomalies more explicitly than the total field. The separation is possible if we can measure not only amplitude but phase of the harmonic components of the magnetic field (three components) and of the source current. In practice, this requires measurements of the magnetic field and of the source current with a high precision of timing which is more demanding than necessary for measuring amplitudes only.

In our experiment, we used the vertical component of the magnetic field because of the following reasons. First, the vertical component was found to be generally stronger than the horizontal component in our survey area. Second, researches in geomagnetic depth sounding indicate that generally an anomalous conductivity structure reveals itself more clearly in the vertical component than in the horizontal component. Nevertheless, it is worthwhile investigating what additional information can be obtained through observation of the horizontal component. In fact, a preliminary study was done by McCOLLOR *et al.* (1982) along this line in the same survey area. In this study, it was found that the ratio of horizontal field strength to vertical field strength varies almost proportionally to the distance from the power line. This trend is consistent with the theory by PRICE (1950) and WAIT (1962), and the apparent resistivity thus obtained is in line with that obtained through the present approach using the vertical component only. The approach of taking the ratio of horizontal to vertical component has an advantage in that the necessity of monitoring changes in source field strength is removed.

The data acquisition system can be improved. The total gain of our preamplifier + recording system is about 80 dB at most. This is a modest gain. The preamplifier can presumably be modified to enhance the gain by 40 dB or possibly 50 dB. The antenna is also small. The antenna size and the wire's turn number can be doubled without losing the portability of our detection/recording system. The absolute sensitivity of the antenna will then be 8 times greater. A solenoid with a high permeability core can make a high-sensitivity, small antenna. However, it has to be investigated carefully whether or not the non-linearity of the high permeability core gives rise to cross-talk among harmonic components. Our data are subject to errors of $\pm 5\%$. It seems that the errors are mostly due to the tape recorders' poor capability in reproducing signals. High performance tape recorders may improve the data quality. The problem may well be resolved using digital recorders instead of analog recorders. However, spectrum analysis of digital data requires a computer which probably makes the data analysis more involved. An adaptive filter designed and built by R. D. Russell and B. N. Narod¹ is especially interesting in this respect. This filter uses 60 Hz signals as a reference. It detects strength of a higher harmonic signal, following any possible fluctuation in frequency. It can also detect the phase shift of the higher harmonic component relative to the reference signal (60 Hz). All these pieces of information can readily be obtained out in the field.

Power system harmonic currents obviously change in intensity, dependent on load. However, they are known to be affected by variations of the Earth's magnetic field as well (ALBERTSON *et al.*, 1973, 1974a, 1974b; BOLDUC and AUBIN, 1977;

¹A personal communication, 1980.

HAYASHI *et al.*, 1978, 1879). Observation revealed that even harmonics are affected by magnetic variations more strongly than odd harmonics (HAYASHI *et al.*, 1978, 1979). Even harmonics become as strong as odd harmonics under conditions of strong magnetic disturbance. It seems that even harmonics are generated through a process as follows. Geomagnetically induced currents flow into a power system through its grounding points and give rise to quasi-d. c. bias magnetic fields to transformer cores. This makes the B - H hysteresis loop of transformer cores asymmetric which yields not only odd harmonics but even harmonics as well (HAYASHI *et al.*, 1979). In this experiment, only odd harmonics were used, as they were strong and stable components. Even harmonics can be used also at a time that they become sufficiently strong. However, they may not be as stable as odd harmonic components in magnetically quiet conditions. It was observed that at a time of magnetic storm, even harmonic components fluctuated in intensity with magnetic field variations of time scales, a few tens of seconds to a few minutes (HAYASHI *et al.*, 1978). Natural radio emissions in the extremely low frequency (ELF) range which originate in outer space of the Earth, are a noise source for the PHM method. It should be examined how serious a noise source they may be. Natural ELF radio emissions are generally enhanced at a time of magnetic disturbance.

Russell¹ pointed out that subharmonic components of power-line magnetic fields might also be usable for E. M. exploration. It is possible to explore a wider and deeper region with subharmonic fields than with highr harmonic components. We were able to detect 30 Hz, 15 Hz, 7.5 Hz and 3.75 Hz components in the A-phase current at Meridian Substation, though they were weaker than the four main harmonic components (60 Hz, 180 Hz, 300 Hz and 420 Hz). However, we could detect no subharmonic componet in the neutral current. The reason why the neutral current subharmonic components are so weak as to be below our detection level remains unknown. In the U. B. C. Research Forest, subharmonic magnetic fields were detected, using a high permeability core coil which was used as a head-sensor of the induction magnetometer system. It is a much more sensitive coil than the antenna used for detecting AF magnetic fields. The coil is about 0.9 m long and has about 10^5 turns of wire winding. The high permeability core is about 1.8 m long. With this coil installed vertically at the base station, we could detect subharmonic components 44 Hz, 30 Hz, 15 Hz, 7.5 Hz and 3.75 Hz without amplifying them at all. Several other subharmonic signals up to about 40 Hz were also detected. Their origins remain unknown. Subharmonic magnetic fields warrant further investigation.

The authors sincerely thank the following individuals and organizations for their assistance which made this research work possible: Dr. K. Tsuruda, Dr. K. Hayashi and Mr. B. E. Chapel in the design and construction of the audio-frequency radio receivers; B. C. Hydro Research Laboratories in the measurement made at Meridian Substation; U. B. C. Research Forest where much of the field work was carried out. The authors also appreciate discussions with Drs. R. E. Niblett, G. D. Garland, R. N. Edwards, A. G. Jones, D. H. Hall, J. J. Lajoie, R.

¹A personal communication, 1981.

D. Russell and B. N. Narod. Assistance from a number of B. C. Hydro staff members and U. B. C. graduate students is also acknowledged. This research work was supported through a Graduate Research Engineering and Technology Award (No. 17 (GC-1)), co-sponsored by the Secretariat on Science, Research and Development of British Columbia and B. C. Hydro and Power Authority and was also supported by U. B. C. Committee on Natural, Applied and Health Sciences (Grant. No. 21-9602).

APPENDIX

Derivation of Eqs. (2) and (3)

It will be explained in this appendix how these two equations are derived from the theory of PRICE (1950) and WAIT (1962). First of all, it should be noted that some of the physical quantities are expressed with different symbols from these two papers. For example, angular frequency is denoted with p in the paper by Price. However, the symbol p stands for skin depth in the present paper. Distance from the power line is expressed with y in Price's paper whereas r is used in this paper.

In the following, the equation numbers refer to those in Price's paper unless otherwise specified. Equation (2) of this paper is based on a result obtained by Price that the induced field becomes negligibly small near the power line. The vertical component of the induced magnetic field is a linear sum of two quantities $Z_1(\xi, \eta)$ and $Z_2(\xi, \eta)$ (see Eq. (10.9)). Both quantities approach zero as $\eta \rightarrow 0$, which means $y \rightarrow 0$. Figure 2 of Price's paper shows how Z_1 and Z_2 approach zero as $\eta \rightarrow 0$. The same result was also obtained by Wait. Reference is made to Eq. (72) of WAIT (1962, p. 27).

Equation (3) of the present paper is derived from Eqs. (10.6) and (10.7). For $z = 0$ and $h \ll y$, equation (10.6) gives:

$$\zeta = i\eta = i\alpha y$$

where α , defined by Eq. (9.6), is $\sqrt{2}$ times greater than the inverse of the skin depth. Price mentions that, for $|\zeta|$ greater than about 6, the induced magnetic field can be given in a form of asymptotic expansion, (10.7). With $\zeta = i\alpha y$, the equation yields:

$$H_z = -2c_0 \frac{\cos pt}{y} + 8c_0 \frac{\sin pt}{\alpha^2 y^3}.$$

The vertical component of the inducing field is expressed as follows, under the conditions that $z = 0$ and $h \ll y$:

$$H_z = 2c_0 \frac{\cos pt}{y}$$

See also the equation in the footnote to page 398 of Price's paper. The sum of the two equations above yields:

$$H_z = 8c_0 \frac{\sin pt}{\alpha^2 y^3}.$$

Equation (3) of this paper is obtained by rewriting this equation in rationalized M. K. S. units. The identical result is obtained as a special case of Eq. (72) of WAIT (1962, p. 27) that $\gamma_1 x$ (the symbols by Wait himself) goes to infinity.

REFERENCES

- ALBERTSON, V. D., R. E. CLAYTON, J. M. THORSON, Jr., and S. C. TRIPATHY, Solar-induced-currents in power systems: Cause and effects, *IEEE Transactions on Power Apparatus and Systems*, **PAS-92**, 471–477, 1973.
- ALBERTSON, V. D. and J. M. THORSON, Jr., Power system disturbance during a K-8 geomagnetic storm: August 4, 1972, *IEEE Transactions on Power Apparatus and Systems*, **PAS-93**, 1025–1030, 1974a.
- ALBERTSON, V. D., S. A. MISKE, and J. M. THORSON, Jr., The effects of geomagnetic storms on electrical power system, **PAS-93**, 1031–1044, 1974b.
- BLUME, L. F., G. CAMILLI, A. BOYAJIAN, and V. M. MONTINGER, *Transformer Engineering*, 37pp. John Wiley and Sons, Inc., New York, 1938.
- BOLDUC, L. and J. AUBIN, Effects of direct currents in power transformers, Part I, A general theoretical approach, Part II, Simplified calculation for large transformer, in *Electric Power System Research*, Vol. 1, 291–298 pp., Elsevier Sequoia S. A. Lausanne, 1977/78.
- DUNCAN, P. M., A. HWANG, R. N. EDWARDS, R. C. BAILEY, and G. D. GARLAND, The development and applications of a wide band electromagnetic sounding system using a pseudo-noise source, *Geophysics*, **45**, 1276–1296, 1980.
- HAYASHI, K., T. OGUTI, T. WATANABE, K. TSURUDA, S. KOKUBUN, and R. E. HORITA, Power harmonic radiation enhancement during the sudden commencement of a magnetic storm, *Nature (Lond.)*, **275**, 627–629, 1978.
- HAYASHI, K., T. OGUTI, T. WATANABE, K. TSURUDA, S. KOKUBUN, and R. E. HORITA, Harmonics of 60 Hz in power systems caused by geomagnetic disturbances, in *Solar-Terrestrial Predictions Proceedings*, Vol. 2, edited by R. F. Donnelly, 172–181 pp., Boulder, Colo., April, 1979.
- MCCOLLOR, D. C., B. E. CHAPEL, T. WATANABE, W. F. SLAWSON, and R. M. SHIER, E. M. Exploration with power line harmonic fields, *EOS, Trans. Amer. Geophys. Union*, **63**, 910, 1982.
- Price, A. T., Electromagnetic induction in a semi-infinite conductor with a plane boundary, *Quart. J. Mech. Applied Math.*, **3**, 385–410, 1950.
- TELFORD, W. M., L. P. GELDART, R. E. SHERIFF, and D. A. KEYS, *Applied Geophysics*, 454 pp., Cambridge University Press, 1976.
- WAIT, J. R., *Electromagnetic Waves on Stratified Media*, pp. 21–27, Pergamon Press, 1962.
- WARD, S. H., AFMAG-airborne and ground, *Geophysics*, **24**, 761–789, 1959.