

POWER LINE INDUCED CURRENT IN THE EARTH DETERMINED BY MAGNETOTELLURIC TECHNIQUES

L. Pellerin, D. L. Alumbaugh, D. J. Reinemann, P. D. Thompson

ABSTRACT. Power frequency (60 Hz and harmonics) AC currents were measured on four Wisconsin dairy farms using resistivity and potential gradient measurements by techniques adapted from magnetotelluric (MT) geophysical exploration. Several measurement sites were located on each farm in addition to a remote site as far away from the nearest power line as could reasonably be achieved. Electric field intensity and earth resistivity measurements were used to calculate the near-surface current density for 60 Hz and the 12 next order harmonics.

Earth currents and the corresponding electrical voltages at 60 Hz and higher harmonics were inconsistent from farm to farm. Electric fields at the farms ranged from roughly 1 to 10 mV/m RMS at 60 Hz, and the current densities ranged from about 5 to 50 $\mu\text{A}/\text{m}^2$, roughly 10 to 1000 times stronger than at the corresponding remote sites. As expected, the presence of 60-Hz power frequency current and its harmonics was stronger near points of electrical use and distribution.

The resulting step potentials, measured with high impedance equipment, were 26 to 8300 times lower than the maximum cow contact voltages prescribed by the Public Service Commission of Wisconsin (PSCW). Assuming a typical reduction of half in the contact voltage with a 500-ohm body impedance the resulting current flow through a cow attributable to earth currents in this study was 50 to 16,000 times below the PSCW action level. Considering the substantial body of literature supporting the PSCW level of concern, the extremely low exposure levels resulting from earth currents would not be expected to cause harm to dairy cows.

Keywords. Animal health, Animal welfare, Dairy farming, Earth currents, Electromagnetic field, Stray voltage.

The term stray voltage refers to a special case of neutral-to-earth voltage that may result in a difference in electrical potential between two points that a cow could contact simultaneously, causing electrical current to flow through the cow. There have been many studies of dairy cattle response to voltage and current exposures (USDA, 1991; NRAES, 2003). This body of research has given rise to standards and guidelines for acceptable levels of contact voltage in animal environments. The USDA group of experts recommended action to keep animal contact voltages below 2 to 4 volts (60 Hz, rms). An action level has been defined by the Public Service Commission of Wisconsin (PSCW, 1996) as exposure to a voltage that could produce a current of 2.0 mA (60 Hz, rms) to flow through a cow. This level was chosen as the lowest level at which some cows might perceive the resulting current flow, and is recognized as being below the level that would produce harm. The electric power supplier may contribute no more than half of this total current/voltage level. The measurement protocol recognized by the PSCW specifies the use of a 500-ohm resistor

across cow-contact points to simulate the combined resistance of a cow's body and the hoof/floor contact. This 2-mA level of concern thus equates to a cow contact voltage of 1 V (60 Hz rms).

"Earth current" refers to a net current flow within the earth. The earth current is a vector quantity related by Ohm's law to potential gradient and bulk resistivity. In terms of physiological effect on cows, earth currents would be of concern if the corresponding potential gradient was sufficient to generate a potential difference between any two contact points greater than the level of concern. It should be understood that, as the potential across the cow can not differ from the potential difference in the earth between her contact points with the earth, there can be no independent effect of induced currents from magnetic coupling with currents in the earth.

There have been persistent concerns among a small percentage of dairy farmers that some harm may be caused to cows subjected to contact voltage/current below the PSCW action level. The small step potentials produced by "earth currents" have been speculated as the cause of poor animal performance. The objectives of this study were to investigate the use of magnetotelluric (MT) methods commonly used for geophysical exploration (Vozoff, 1991) for directly measuring power frequency electrical currents flowing in the earth and to better understand the contribution of these earth currents to the electrical environment of farm animals. Classic magnetotelluric (MT) methods determine the earth's subsurface resistivity by measuring naturally occurring low frequency electromagnetic waves. In this study, high sensitivity magnetotelluric equipment was used to obtain measurements of potential difference and resistivity, from which the magnitude of the earth current vector was

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calculated. In a future study, we plan to use magnetotelluric instruments to measure the H-field at the earth's surface, which will provide an independent indication of the earth current.

METHODOLOGY

Measurements were obtained at two groupings of two farms each. One group was centered around Dane County, which was convenient and is one of Wisconsin's larger dairy counties. A second group was in Marathon County, which has the state's largest concentration of dairy farms and is also a source of concerns about earth currents because of a proposed transmission line to be built in this area. A remote site was chosen for each group of dairy farms to determine the level of background signal, which is relatively uncontaminated by power-line-induced signals. Although we made measurements at specific times and locations, our measurements cover the range of conditions expected on Wisconsin dairy farms.

Modifications to the MT methods used in geology were necessary to make these methods suitable for the signal levels experienced on the farm. Four MT24 systems from Electromagnetic Instruments, Inc. (EMI) were used for the data acquisition. The MT24 has 24-bit resolution that enables the measurement of fields over an amplitude range of eight orders of magnitude. Electric field (E-field) measurements were made by recording potentials observed from orthogonal dipoles, each dipole connected to an electrode pair using non-polarizing, porous-pot electrodes (half-cells) as earth contacts. The contact resistance between the porous pot electrode and the soil should usually be under a few thousand Ohms. This source resistance in series with the input resistance of the data acquisition system of well over one M-ohm means little attenuation of the signals occurs. The electrodes and coils are connected to field acquisition modules (FAMs) that digitize and amplify the measured voltages. The signal is then fed into a central storage unit for archiving. All system and survey parameters are stored and controlled through a laptop computer that is connected to the CSU and the GPS clock.

In conventional geological E-field measurements, each dipole would have a length of 100 m, and this length was used at our remote sites. On-farm measurements were made using 20-m dipole length, allowing for the higher on-farm voltages without saturating the instruments. For both the remote and on-farm, voltages from both dipoles of each orthogonal pair were recorded as field strength in mV/m, and measurements from the two dipoles were added vectorially, yielding a single reading from each dipole pair. Vector data permit determination of the orientation as well as the amplitude of the E-field vector.

At each farm and the remote sites, soil resistivity was determined by injecting low-frequency (essentially DC) current through ground electrodes separated by 3 m. The voltage was measured at potential electrodes, separated by 1 m, and centered on the axis defined by the current injection electrodes. As shown in table 1, an apparent bulk resistivity of the near surface, of approximately 1-m depth, is computed from the ratio of measured voltage to injected current, with an appropriate geometric factor. Earth currents were calculated from the measured E-field and earth resistivity estimates. In accordance with Ohm's law, earth current density was computed by dividing E-field measurements by the earth resistivity. This calculated current density is a mean value over the dimensions of the electrode array, but is appropriate, as these dimensions approximate those of a cow.

E-field data were sampled for 250 s, at a sampling rate of 2000 samples/s. The data were then converted to a frequency amplitude spectrum using the Fast Fourier Transform (Math Works, 1998). The amplitude peaks at 60 Hz and the next 12 harmonics (120 Hz, 180 Hz, etc.) were tabulated. Measurements on one farm were made simultaneously at the corresponding remote site, the measurements being synchronized using global positioning system (GPS) clocks. Measurements were made at two or more locations on each farm and data were recorded under several electrical use conditions. Simultaneous measurements were made at the corresponding remote location during the farm tests.

RESULTS

SPECTRAL ANALYSIS

Representative spectra from simultaneous farm and remote recordings are shown in figure 1. Clear peaks are apparent at 60 Hz and its harmonics that are generally one to three orders of magnitude larger than background levels. This illustrates that the predominant electrical signals detected were derived from 60-Hz sources. In all cases, the 60-Hz amplitude was the strongest and generally an order of magnitude greater than any of the harmonic frequencies. The amplitude of the harmonics generally decreased with increasing frequency, and the odd harmonics (3rd = 180 Hz, 5th = 300 Hz, etc.) were stronger than the even harmonics (2nd = 120 Hz, 4th = 240 Hz, etc.).

REMOTE CURRENT DENSITY

The signals at the two remote sites were significantly different from each other. The Marathon County remote was approximately 1 mile from the nearest transmission, or distribution line, whereas the Dane County remote was approximately 0.5 miles from the nearest power line.

Table 1. Characteristics of farms and remote sites.

	Dane Farm 1	Dane Farm 2	Dane Remote Site	Marathon Farm 1	Marathon Farm 2	Marathon Remote Site
Electrical Service	3 Phase Open Delta Underground	Single Phase Overhead	NA	Single Phase Overhead	Single Phase Overhead	NA
Equipotential Plane	Yes	Yes	NA	No	No	NA
Earth Bulk Resistivity (ohm-m)	50	13	1068	51	238	221

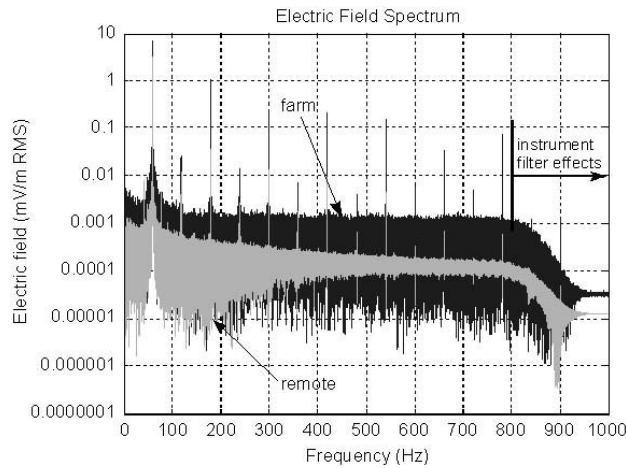


Figure 1. The electric field spectrum for a representative farm and remote site recorded simultaneously with a 2000 samples/s sampling rate.

Nevertheless, the signal amplitudes at the Marathon County remote were two orders of magnitude greater than those at the Dane County remote. The highest 60-Hz signals observed at a remote site were an E-field of 0.53 mV/m and a current density of 2.41 $\mu\text{A}/\text{m}^2$, observed at the Marathon County remote while measurements were being taken at Marathon County Farm 2. The lowest remote levels at 60 Hz were 0.012 $\mu\text{V}/\text{m}$ and .012 $\eta\text{A}/\text{m}^2$ at the Dane County remote simultaneous with measurements at Dane County Farm 2.

There are several possible reasons for this: the contribution from the power lines can be appreciably different, and the Dane County data were collected in the summer and fall in contrast to the Marathon County data that were collected in summer only. The Dane County site had a higher earth resistivity, possibly a result of seasonal variation in soil moisture.

The current densities at the remote sites were always lower than at the corresponding farm sites. The magnitude of the difference varied from about one order of magnitude when comparing the electrically quiet Marathon County farms with the corresponding remote, to over three orders of magnitude when comparing the relatively noisy Dane County Farm 1 with its remote. An example from Marathon County Farm 1 (fig. 2) shows increased current density when the farm load is turned on, and the difference of about one order of magnitude between the on-farm levels and those at the remote.

ON-FARM CURRENT DENSITY

At each of the four farms, field strengths were measured under multiple conditions of load, and on three of the farms, measurements were also replicated with the farm “isolated,” meaning that the power system neutral (the grounded conductor of the utility distribution system) was disconnected from the farm neutral. For 60-Hz measurements, increasing farm load increased the observed E-field. However, the effect of isolating the neutral was not consistent. Neutral isolation might increase, decrease, or have no effect on field strengths. The amplitudes of E-field detected at the Dane County Farm 2 barn site are illustrated in figure 3. The freestall barn has an equipotential plane. There is a family of observations at 60 Hz and at 12 harmonics of 60 Hz. Within the family of observations at each frequency, individual bars

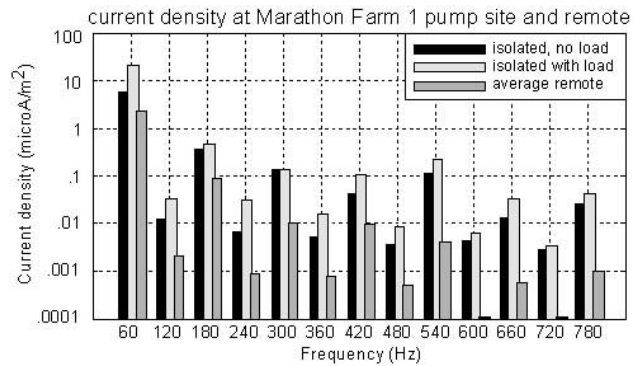


Figure 2. Total current density bar plot for Farm 1, Marathon County, site 203, for the minimum condition of the farm isolated with no load, the maximum condition of isolated with a load, and the average value for the corresponding remote site at Smokey Hills.

represent different combinations of load and neutral isolation. Within the 60-Hz family, it can be seen that for the E-field, amplitude is greater when the neutral is “non-isolated” rather than when “isolated,” regardless of the load. It can also be seen that among the “isolated” readings, the E-field increases with increasing load, as it also does among the “non-isolated” readings.

The effects of isolation and load at the individual farms were as follows:

Dane County Group

Farm 1. At 60 Hz the non-isolated responses were about 3 mV/m RMS less than when isolated. The farm contribution was about 2 to 3 mV/m RMS. Doubling the load increased the field 3 to 4 mV/m RMS.

Farm 2. Electrical voltages in the earth due to the distribution network were about 2 to 3 mV/m RMS at 60 Hz, and the farm contribution was about 3 to 4 mV/m RMS at 60 Hz. There is a difference of about 2 mV/m RMS between the isolated and non-isolated conditions with or without a load, with the non-isolated being greater.

Marathon County Group

Farm 1. The contribution of the earth voltage due to the farm is about 3 mV/m RMS at 60Hz and the contribution due from the electrical distribution system about 3 mV/m RMS

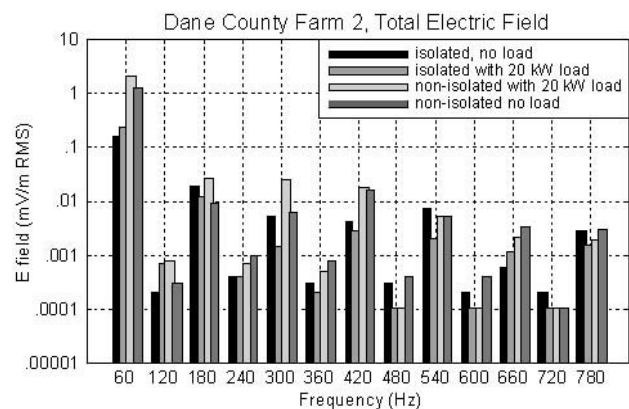


Figure 3. Total electric field values for 60 Hz and the next 12 order harmonics for Dane County Farm 1 at the site near the transformer.

at 60 Hz. There was no significant difference between the non-isolated and isolated conditions, nor was there a dominant equipment response.

Farm 2. There is less than 2-mV/m RMS variation in electric field value at 60 Hz for all conditions but the farm on with the 25-kW load box, which added about 2 mV/m.

Among all of the farms and load conditions, the highest readings at 60 Hz were an E-field of 25 mV/m and a current density of 492 $\mu\text{A}/\text{m}^2$ obtained at the Dane County Farm 1 milking parlor site while the farm was operating at normal high load operating condition. The minimum e-field observed was .083 mV/m at the Marathon County Farm 1 milking parlor with loads off and the farm non-isolated. The minimum current density was 1.55 $\mu\text{A}/\text{m}^2$ observed at Marathon County Farm 2 milking parlor site with only fans running.

CONCLUSIONS

Earth currents and the corresponding electrical voltages at 60 Hz and its next order harmonics demonstrated an inconsistent relationship to the remotes at all farm sites. The results from adding load through a load box, or operating various machinery combinations were inconsistent from farm to farm making generalized comparisons not possible. Electric fields at the farms range from roughly 1 to 10 mV/m RMS at 60 Hz, and the current densities ranged from about 5 to 50 $\mu\text{A}/\text{m}^2$. Because of the nearness of the power supply, average values at the farm are roughly 10 to 1000 times stronger than at the corresponding remote sites. Comparison of signal strength from the two remote sites shows that variations in the natural field and contributions from distant manmade structures can be significant. Even though man-made signals were larger than the naturally occurring currents, the step potential levels are a very small fraction of the action level established by the PSCW. Only the E field data are being used at this point in the study and therefore we cannot resolve the source of the currents. However, we hope to pursue future studies to analyze the magnetic field measurements that will provide insight into the types of sources.

Hendrickson and Patoch (1998) measured “step potentials” at 1.5-m electrode separations on 19 Minnesota farms. The 1.5-m separation distance was used to approximate the potential developed across the front-rear hooves pathway for a dairy cow. The 1.5-m step potentials reported by Hendrickson and Patoch (1988) ranged from about 1 to 50 mV in the farmyard, and 0 to 12 mV in fields near the farms. The corresponding potentials across a 1.5-m step distance

estimated from the earth resistivity measurements and calculated current densities in our study ranged from 0.12 to 38 mV for a 1.5-m step distance, and thus compare well to the values reported by Hendrickson and Patoch (1998). It should be noted that in both studies, step potentials were measured with high impedance equipment, giving “open circuit” readings. A 500-ohm load, as is used for stray voltage investigations, reduced these readings to about half in Hendrickson and Patoch (1998), and would be expected to have a similar effect in our study. Hendrickson and Patoch (1998) also observed relatively high odd harmonic content of the voltages analyzed, as did we.

The open circuit step potentials attributable to earth currents we measured are 26 to 8000 times lower than the conservative action level prescribed by the PSCW. Assuming a typical reduction of half in the contact voltage with a 500-ohm body impedance the resulting current flow through a cow attributable to earth currents in this study was is 50 to 16,000 times below the PSCW action level. Considering the substantial body of literature supporting the PSC level of concern, the extremely low exposure levels resulting from the earth currents we measured would be expected to cause harm to dairy cows.

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