THE NATURE AND VARIABILITY OF GROUND CURRENT AS A SOURCE OF RESIDENTIAL MAGNETIC FIELD

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ABSTRACT

Net currents on power cables and water lines are analyzed in terms of those characteristics that might be germane to magnetic field exposure, when there are questions about the appropriateness of metrics or even the association between magnetic field exposure and health effects. The paper focuses on magnetic field aspects of uniformity in space and constancy in time important to exposure assessment. The spike-like nature of these magnetic field intensities is addressed, and relevant literature on such transients is reviewed.

INTRODUCTION

A major shortcoming in the postulate that exposure to power frequency magnetic fields has an effect on human health is that there is not yet a mechanistic explanation for their interaction with biological structures that has scientific acceptance. Traditional physics is skeptical of these suppositions, while biological science pursues leads pointing to animal perceptions and general physiological effects at these low frequencies. Not knowing the mechanism makes it difficult for scientists and engineers to define magnetic field metrics. The classical engineering characterizations have been adopted by default. The most readily available measurement, for example, is the root-mean-square of the resultant magnetic flux density at a point in time and space. However, the field is actually a complex vector quantity with many other parameters [Ref. 1].

The type of metric used to characterize magnetic fields is indeed part of the research problem. Some epidemiologists have focused on surrogates that relate the present health effect to an exposure that occurred many years earlier (for diseases such as cancer with etiological developments that take many years). Some of the surrogate measurements used include wire codes, distance from power lines, and historical records of power line loads. Spot measurements of power-related magnetic fields fail to correlate with the incidence of the same diseases. The implications are that either the epidemiological results are artifacts, probably due to confounders or an unknown factor, or that the contemporary measurements examine the wrong parameters. The use of field intensity to characterize the magnetic field exposure remains, neverthe less, the main measurement. This obscures the fact that there are other metrics for magnetic field exposure that may be more appropriate. This is the case for "ground currents" on water lines where there may be other aspects more important for exposure assessment than field intensity.

Residential plumbing has been identified as a source of power-frequency magnetic field and has been characterized as a pervasive factor [Refs. 2 and 3]. Plumbing tends to be downplayed because the associated magnetic field is often below the level considered safe (2 mG). By comparison, an electric razor generates intense magnetic fields, and its use is considered by some a much higher risk. This is, however, based only on field intensity. If the effect is assumed to be cumulative [Ref. 4], a more appropriate metric might be the time integral of intensities. For example, if an electric razor generates a field of 100 mG (6 inches away), a 2-minute daily use would provide a cumulative exposure of 3.3 mG·hr/day, while a water line carrying power line current that generates 1 mG (6 ft away) would provide a cumulative exposure of 24 mG·hr/day. The water line magnetic field becomes a much higher risk element in the cumulative exposure metric. Of course, if the health effect were based on a threshold or window effect, the metrics would change accordingly. One note of caution resulting from all this is that present judgments and risk perceptions can be flawed because of other unknowns regarding the postulated causality link between power-line magnetic fields and health effects.

This paper addresses the magnetic field associated with residential plumbing. It builds on a previous study [Refs. 5 and 6] of a field investigation to address "ground currents," water lines, and power lines. Many new facts came to light in that work. One of the more interesting was that the nature of water service, well versus municipal system, itself may be a new surrogate measurement for historical magnetic field measurement. This is indeed the case made by Wertheimer et al. in a recent paper [Ref. 7]. Many other questions, however, were also raised in that previous study. These relate to the source of these currents, the variability in space and time, and the frequency content. These are very important questions for assessing magnetic field exposure as well.

SOURCE DESCRIPTION

"Ground current" has been used repeatedly in EMF publications to refer to the current on water lines. It can be confusing when others use the same term to refer to either current in the earth or current on grounding electrodes. To further confuse the matter, water lines are both circuit conductors and grounding conductors. Considering the many studies and publications with differing terminologies on the subject, there is a need to clarify the terms and define the currents.

A diagram is shown in Figure 1 that outlines the two most common forms of residential power services, connected to a multigrounded wye power distribution line, and a municipal water distribution system with a service line to each residence.

The distribution line neutral conductor (primary), the service cable neutral conductor (secondary), the neutral wire in each residence, the residential plumbing, and the municipal water system are all interconnected and form an extensive network of electrically conductive looping pathways, often referred to as the grounding network. In actuality, the web of electrical pathways is made more complex by the sheer number of services, especially in congested environments such as cities. We have seen that this leads to some benefits, such as effective residential grounding systems in cities [Ref. 5].

The primary and secondary sides of a service transformer form two separate circuits magnetically coupled at the transformer. Primaries are usually connected between a phase wire and the neutral wire on the distribution line. This causes a load current to flow on the distribution line neutral conductor. On a three-phase distribution line, service transformers are typically hooked to different phase wires to spread the load and balance the line. Seen from the source, on a long line that includes many service transformers, the result is that the load current on the neutral conductor tends to be canceled by the balancing and the nature of three-phase power transmission. Near the customer, however, this load current is present on the neutral conductor and is often referred to as the "imbalance current." This primary imbalance current flows on the power line distribution neutral conductor in returning to the source or before being canceled by the three-phase balancing. It can also flow on the grounding network, through the earth using various groundings as the earth entry and exit points, or along any mixed paths in the grounding web.

The secondary circuit of a service transformer is a center-tapped winding with a three-wire service drop. The center tap is grounded and referred to as the secondary neutral. It is bonded to the line neutral conductor at the transformer and to the residential plumbing on the customer premises. The three-wire system provides a 240-volt circuit between the ungrounded conductors, and two 120-volt circuits, each between one of the ungrounded conductors and the secondary neutral. Load current on the secondary neutral is limited to that portion that does not cancel out (imbalance) between the two 120-volt circuits, a situation much like the one on the distribution line. Because the secondary neutral is part of the grounding web, this secondary imbalance current can follow any path in the web that provides the least impedance; this includes water lines, neighboring residences, and the distribution line neutral conductor.

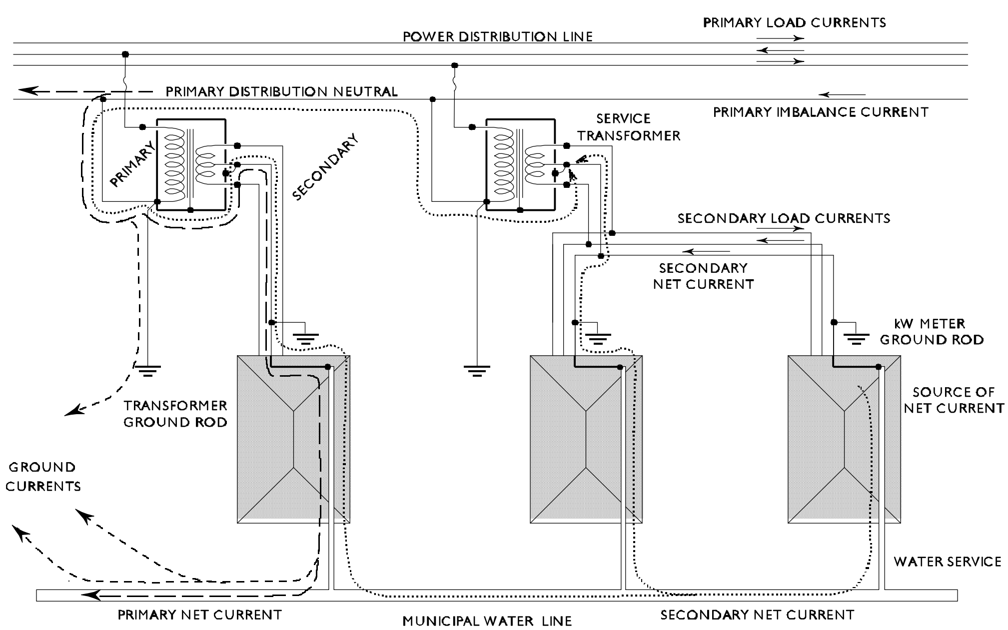

Figure 1. Typical power services and net currents on water lines.

Currents on a power supply cable balance out to form a vectorial zero-sum. Put simply, whatever current flows toward the load has to return to the source, causing a net current of zero on the supply cable. However, the presence of the grounding web causes portions of the imbalance currents to be diverted from the neutral wire, and to return to the respective source through the plumbing or other connections on the grounding web. The power supply cable will show as missing a portion of the imbalance current, resulting in net current on the power supply cable, the same as is found on the plumbing or dispersed in the grounding web.

The primary and secondary circuits are identical in terms of each having a grounded conductor (neutral). Net current can occur on both the primary and secondary sides of a service transformer; thus, these currents are referred to as primary and secondary net currents. They get mixed and dispersed on the grounding web. These are the currents of interest in this paper, where they are referred to as net and water line currents.

Ground currents are those that flow into or out of the earth through a grounding element such as a ground rod. There are also many unintended grounding elements such as water lines, which are excellent grounding systems. There is, however, always a bit of resistance associated with these grounding systems that is dependent on the earth conductivity. This is typically enough to limit the intensity of these ground currents, especially as compared to continuous metallic paths on the grounding web. These currents are not addressed here, nor are currents in the earth.

SPACE VARIATIONS

There are two features of net and water line currents that make the associated magnetic field a serious exposure factor compared to other, more intense field sources. They are: a slow dropping off of the field as the distance is increased from the source, and the ubiquitous presence of the source in the residential environment.

The rate at which a magnetic field drops off from its source is important because it affects the average field intensity in the environment, which, coupled with the time-activity, determines the exposure factor. The spatial falling off of the magnetic field from different sources has been reported by various authors [Refs. 3 and 8]. The sources have been categorized as: (1) point sources, which follow a cubic field-versus-distance falling-off relationship; (2) line sources, which follow a square falling-off relationship; and (3) open loops, which follow a linear falling-off relationship (see Figure 2). Appliances have magnetic fields that typically drop off following a cubic rate, transmission and distribution lines have magnetic fields that typically drop off following a square rate, and net and water line currents are good examples of sources with magnetic fields that drop off linearly.

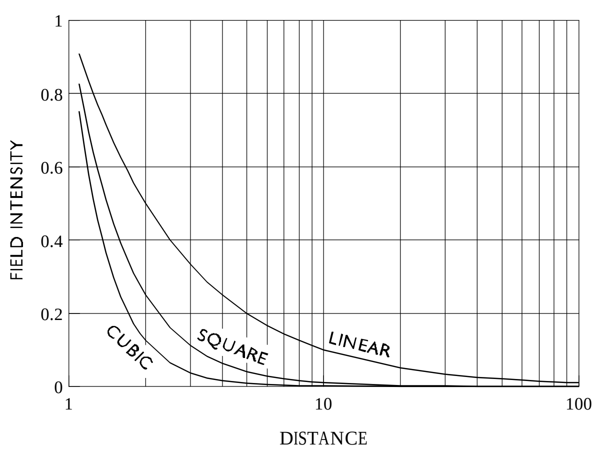

Figure 2. Comparison of typical magnetic field falling-off rates.

Figure 2 compares these three relationships. Linearly dropping fields are more intense at greater distances from the source and contribute, more than other source types, to the "filling" of the environment with magnetic field. Figure 2 shows that the slope initially changes little for all three relationships, down to the point where the field drops to about 20% of its initial value. In this region, the field changes nearly three times more slowly with the linear relationship than with the cubic relationship. It changes slightly more than twice as slowly when the linear relationship is compared to the square relationship. This means that an individual could move in a linear-decaying field nearly three times farther than in a cubic-decaying field before experiencing the same change in magnetic field. This is a very important factor in establishing exposure and risk.

To put these relationships in perspective, an electric razor, for example, will create an intense field near and inside the head, when held in a shaving position, but insignificant fields in the lower portions of the body. Transmission line fields are seen, on the other hand, as sources that provide a nearly uniform field over the entire human body. Water line and net current fields are even more uniform, and not only over the body of a person, but as he moves about, within a certain space as well. These spatial variations have a significant value for exposure assessment and risk analysis.

Net currents flowing on overhead drop cables, at the back of the house, and then on water lines, at the front of the house, provide a longitudinal uniformity effect (see Figure 3) much like that of driving on a highway parallel to a transmission line. In measuring the field at 1 meter above ground, the distance from the secondary net current is nearly the same whether the conductor is the overhead cable at the back of the house or the buried water line in front of the house. The point 1 meter above ground is a point of epidemiological interest, and also happens to be nearly midway (about 9 ft) between the height of power drop cables and the burial depth of water lines. The field right under the drop cable or over the water line at the standard 1 meter will actually vary somewhat because the cable height varies along the length due to sag, and water line depth can also vary from the house to the main in the middle of the street. If this distance varies within a 25% range, the corresponding magnetic field right under the cable or over the water line will also vary within a 25% range. But the field also drops off laterally from the drop cable and water line. Measured at 1 meter above ground, this field will drop to 25% of the peak field, right under the drop cable or right over the water line, at about 8 ft to the side. A tract 16 feet wide exists then, running in back of the house under the drop cable and in front of the house over the water line, where the field does not vary by more than 25%. A similar situation exists inside the residence as well, although the distance will be different and the net current path may be distributed.

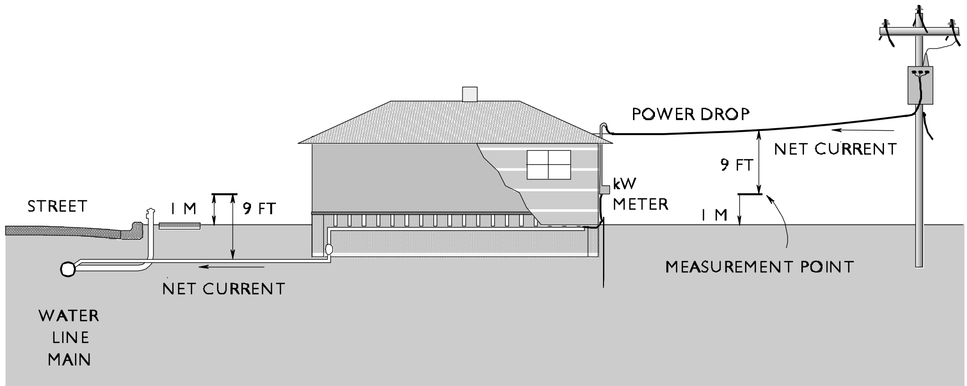

Figure 3. Components of uniform exposure along path of net and water line currents.

There is another aspect of net and water line currents that contributes further to the filling effect of the magnetic field in the space around the residence: the cumulative effect of many such sources in the neighborhood. The web created by power and water services at each residence, coupled with their respective distribution lines (see Figure 1), creates many sources whose effect is integrated at any single point.

TIME VARIATIONS

The time variation of magnetic fields associated with net and water line currents is also unique and an important factor to study (see Figure 4). There are two aspects of interest: one of these is time variation as it affects exposure, and the cause and sources for this variability; the other is rapid changes, or transients, which lately have been of interest to researchers.

Figure 5 compares samples from various sources of power-frequency magnetic field, along the categorization discussed earlier. The magnetic field associated with net current and water lines has its own signature. It is characterized by continuous and seemingly random spike-like changes. By comparison, the magnetic field associated with power transmission and distribution lines is much more steady and continuous. Only the magnetic fields of some appliances come close to the water line magnetic field in terms of variability.

The continuous rapid variations result from the integration of many randomly switching loads, both inside the residence of interest as well as in neighboring residences, and from the accompanying transients. Mader and Zaffanella [Refs. 9 and 10] have developed mathematical models that successfully replicate these phenomena on a small scale. Both primary and secondary net currents can be present. The presence of electrical discontinuities or lumped resistances at joints or electrical connectors will also contribute to the pattern of these currents in the neighborhood and the intensi-

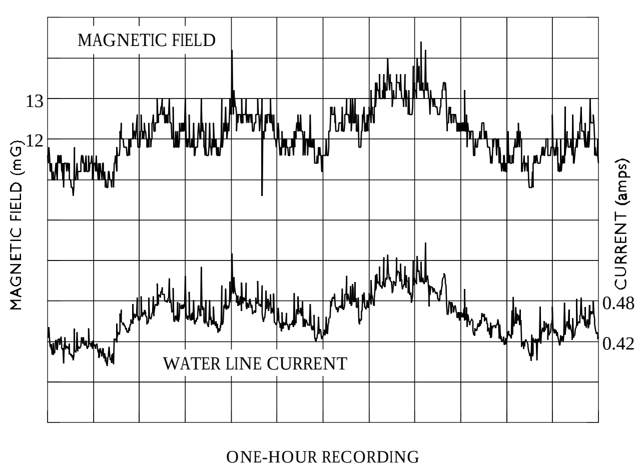

Figure 4. One-hour recording of current on water meter and magnetic field nearby.

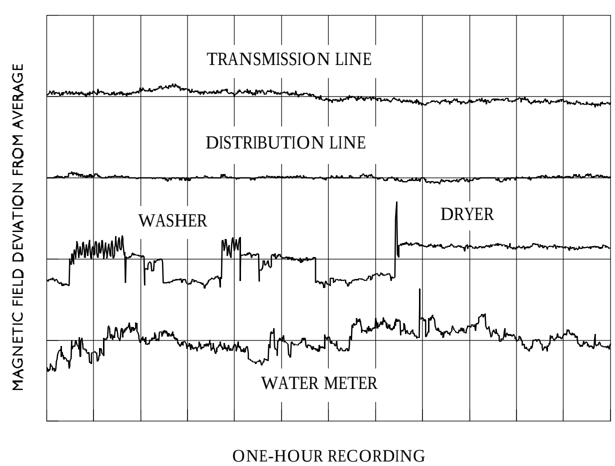

Figure 5. Comparison of one-hour recordings for various magnetic field sources.

ties in a specific residence. What is not clear is whether there is a prevalent pattern; that is, the extent that current inside a residence is affected by load activities inside the residence versus load activities in neighboring residences and on power lines.

The spike-like nature of this magnetic field and its unpredictability have caused a number of difficulties in assessing exposure. The spikes, however, may not have much impact in exposure assessment–except as will be discussed later in terms of transients–because of the complex activity patterns of individuals, which can create time changes in exposure that are just as spike-like. What may be more significant for exposure assessment is the presence of a constant, bulk magnetic field rather than the spikes. Figure 6 is a sample of water line current recorded over a seven-day period. The current on the water line clearly shows both a constant average component and a cyclical daily variation. In general, this magnetic field can indeed be separated mathematically into three components that are linearly added to form the total pattern: a long-term component (daily average); a slow-changing component that completes a cycle every day (hourly moving average); and instantaneous changes (spikes).

FREQUENCY SPECTRUM

Transients have become of interest in EMF research in recent years; indeed, it is suspected that transients may be responsible for the bone-healing therapeutic effects of magnetic fields [Ref. 11]. Transients occur naturally as linear loads are switched on and off on the power line, or continuously during the operation of nonlinear loads, which have become very common in recent years. The spike-like nature of the magnetic field related to net and water line currents, discussed earlier, is in part related to the transients associated with load switching. There are innumerable types and forms of transients, each device and application having signature-like characteristics. A more useful approach is to consider the frequency domain and the way various sources contribute to this frequency spectrum.

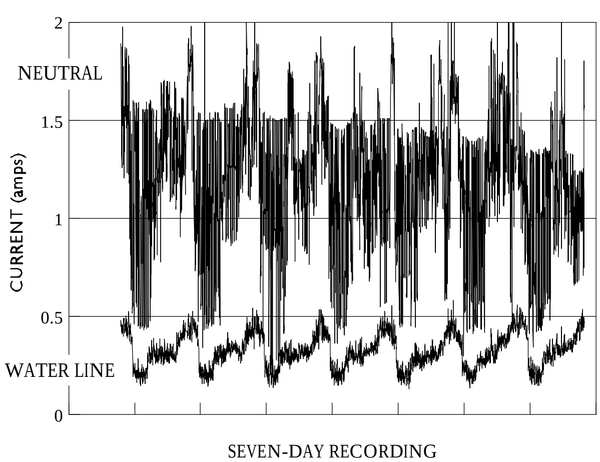

Figure 6. Sample of seven-day recording of current on drop neutral and water meter.

As explained earlier, net and water line currents result from a number of sources and circumstances. Compensating capacitor bank switching, line disconnecting, faults, and other operations on the distribution line are among the more common causes of transients whose effects are conducted inside and just outside the residence on the grounding web. Inside the residence, the source and occurrence of transients is even more pervasive. Vines et al. [Refs. 12 and 13] studied the frequency spectrum between 0 and 100 kHz on the residential power circuit. The spectrum was divided into four categories: (1) *harmonic frequencies synchronous with the fundamental power frequency*, such as those created by silicon-controlled rectifiers and switching power supplies, very common nowadays; (2) *continuous and uniform frequency spectra* (much like white noise) created by universal motors, also very common with the many appliances and power-tools; (3) *single event frequencies*, associated with the starting of specific large loads, such as air conditioners; and (4) *harmonic frequencies not synchronous with the power frequency*, such as those related to the vertical scan frequency of television receivers (15,734 Hz).

Vines et al. found that universal motors such as those used in portable power drills, silicon-controlled rectifiers such as those used in light dimmers, and television receivers are the main causes inside the residence for the observed frequency spectrum on residential power circuits up to 100 kHz. Fluorescent lights, typically a strong source of magnetic field, generate comparatively low levels of high frequencies.

Interestingly, the frequency spectrum on the residential 120-volt line was found to be nearly flat, dropping linearly by about 20 dB at the higher end. It was also found that some of these high frequency signals propagate to neighboring residences, but with some attenuation. The propagation occurs through the grounding web, on the power and water lines. The impedance of the wires and lines between homes at the higher frequencies tends to provide a buffering effect. By the same token, it was also observed that a resonance condition exists, especially above 40 kHz, that will enhance the signals at those frequencies.

Contrary to what happens with 60-Hz power currents, which tend to balance and cancel out, causing relatively small remnants in the form of imbalance and net currents, most of these harmonics and higher-frequency components will appear on the neutral and grounding conductors and give that spike-like and seemingly random look to the current and magnetic field on water lines. The currents at the higher frequencies are, however, much less intense, by as much as 30 to 50 dB, than those at the basic power frequency.

Conclusions

If the link between power-frequency magnetic fields and health effects is demonstrated scientifically, net and water line currents are most likely to be important sources, because of the pervasiveness and time characteristics of their associated magnetic fields.

The sources of water line magnetic field have been identified as net currents resulting from imbalance currents in the presence of competitive paths on the grounding web. The currents can originate on the distribution line (primary net currents) or on the service cables (secondary net currents). The relative intensity of these currents is determined principally by the characteristics of power circuits and the presence of conductive water supply lines, and less importantly by power loading. The field associated with net and water line current sources is very pervasive, because of its slow rate of dropping off, geometrical circumstances between the burial depth of water lines and the elevation of power drop cables, and also because of the ubiquitousness of power cable and water lines in and around the residence. The spike-like nature of time variations of these fields has been discussed and related to the transient issue. It has also been pointed out that notwithstanding the spikes, there are components in the field that provide both long-term constant exposure and predictable cyclic variations.

These fields and their sources have many interesting facets and much more complex details that deserve further study. The lack of a demonstrated interaction mechanism between magnetic fields and effects, and the associated lack of knowledge of what may be relevant about these fields, are even more important reasons to intensify research efforts in these fields.

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