Development of Differential Magnetic Field Methodology for Estimating Quantity of Stray Current Carried Through Conductive Earth

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Abstract: ***This paper describes the development of a measurement methodology based on differential magnetic field measurements, capable of providing quick and practical estimates of the amount of stray current propagated through subterranean electrically conductive deposits.***

Keywords: Stray current, electromagnetic field, magnetometer measurement, conductive earth, biological impact

1. Introduction

Ground-borne stray currents represent an increasingly recognized form of environmental pollution, with compensation awards in such cases exhibiting near-exponential growth in recent years (1).

As these currents typically propagate through aquifers, water-saturated soils, or small, previously uncharted deposits of carbon, ocher, or iron ore in underground strata, it has been difficult to quantify the amount of stray current either emanating from a source or flowing toward a specific site.

By employing sensitive magnetometer instrumentation and combining single-axis with differential-topology measurements, a robust field methodology has been developed that enables precise estimation of stray current magnitudes propagating through subterranean conductive media.

2. Literature Survey

While values in modern, decentralized electrical infrastructures may vary depending on system configuration, earlier research indicates that approximately 65–75% of the return current is carried through the earth rather than via dedicated return conductors (2, 3, 4).

In previous studies we have investigated the adverse effects of stray currents on both plants (5) and farm animals (6), and examined how vortex-like field topologies (7, 8), arising from phase interactions and reflections at subsurface impedance discontinuities, may shed light on the underlying mechanisms responsible for such negative biological effects on animals.

However, there appears to be no prior research specifically focused on quantifying the magnitude of stray current propagated through underground conductive deposits.

3. Problem Definition

The present study introduces the development of a measurement methodology based on magnetometer readings, capable of quantifying the magnitude of stray current carried through conductive deposits in underground strata.

4. Methodology

4.1 Biot-Savats Law

While we may begin by recalling Maxwell–Ampère’s Law (9, 10, 11),

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

which describes how the magnetic field circulates around electric current and changing electric fields, it is Biot–Savart’s Law (12) that proves more practical for field-based current estimation. Although it can be derived from Ampère’s Law under magnetostatic conditions, Biot and Savart originally formulated it empirically (13), well before the advent of Maxwellian theory.

$$\mathbf{B}(r) = \frac{\mu_0}{4\pi}\int \frac{\mathbf{I}\, d\mathbf{l}'' x (r - r')}{|r - r'|^3}$$

The Biot–Savart Law as originally derived assumes that the current **I** is steady, that the magnetic field response is instantaneous and it furthermore ignores displacement current, retardation effects, and wave propagation.

While the Biot-Savart law is strictly valid only in magnetostatics from a theoretical perspective, in practice it proves a worthwhile approximation for AC, as long as the quasistatic approximation holds. That is: The fields vary with time, but slowly relative to the speed of light propagation across the system, retardation can be neglected and displacement currents (i.e. $\partial t/\partial E$) contribute negligibly to the magnetic field in near-field zones.

For 50hz and its harmonics, we can therefore use Biot-Savats law to quantify the current from measurements of the magnetic field.

Now consider a long, straight wire carrying current **I** along the *z*-axis and an observation point at a perpendicular distance *R* from the wire (in the *xy*-plane).

We define **r** = (x,y,0), current path: **r′** = (0,0,z′), distance vector: $\mathbf{r}-\mathbf{r}'=(x,y,-z')$ and $d\mathbf{l}'=dz'\,\hat{\mathbf{z}}$

Rewriting, we get:

$$\boldsymbol{B}(r)=\frac{\mu_0 \boldsymbol{I}}{4\pi}\int_{-\infty}^{\infty}\frac{dz'\,\hat{\boldsymbol{z}}\times(x,y,-z')}{(x^2+y^2+z'^2)^{3/2}}$$

We compute the vector cross product:

$$\hat{\boldsymbol{z}}\times(x,y,-z')=\begin{vmatrix}\hat{x} & \hat{y} & \hat{z}\\ 0 & 0 & 1\\ x & y & -z'\end{vmatrix}=(y\hat{x}-x\hat{y})$$

So the integrand becomes:

$$\frac{y\hat{x}-x\hat{y}}{(x^2+y^2+z'^2)^{3/2}}$$

Since this expression is independent of z′ in the numerator, we can take the constant factor out of the integral:

$$\boldsymbol{B}(r)=\frac{\mu_0 \boldsymbol{I}}{4\pi}(y\hat{x}-x\hat{y})\int_{-\infty}^{\infty}\frac{dz'}{(x^2+y^2+z'^2)^{3/2}}$$

Let $R^2=x^2+y^2$. Then:

$$\int_{-\infty}^{\infty}\frac{dz'}{(R^2+z'^2)^{3/2}}=\frac{2}{R^2}$$

And:

$$\boldsymbol{B}(r)=\frac{\mu_0 \boldsymbol{I}}{4\pi R^2}(y\hat{x}-x\hat{y})$$

Which finally gives us a circular magnetic field, tangent to circles around the wire, with magnitude:

$$(B)=\frac{\mu_0 I}{2\pi R}$$

Solving for **I**, so that the current can be calculated from a measured magnetic field **B** at a distance R:

$$I=\frac{2\pi R B}{\mu_0}$$

This provides us with the possibility of calculating the current propagated along a long and thin filament of electrically conductive deposits underground.

a) **Centerline position of conductive deposits**

It is still necessary, however, to determine the precise position and depth of such electrically conductive deposits.

To estimate the horizontal position, horizontal differential magnetometer measurements are employed.

The magnitude of the spatial gradient of the magnetic field is given by:

$$\left|\frac{dB}{dr}\right|=\frac{\mu_0 I}{2\pi r^2}$$

This implies that the quantity *ΔB/Δr* is maximized when r is small. Therefore, by observing the point of steepest gradient, the centerline of the underground current-carrying deposit can be accurately located using differential magnetometer techniques.

b) Depth of conductive deposits

The vertical depth of the current-carrying deposit can likewise be determined using differential magnetometer measurements, this time with the instrument oriented vertically.

If the deposit is located at a depth d, and measurements are taken at heights h1 and h2, the respective distances from the deposit are given by:

$$r_1=\sqrt{d^2+h_1^2}$$

$$r_2=\sqrt{d^2+h_2^2}$$

The magnetic field at each point is

$$B_1=\frac{\mu_0 I}{2\pi\sqrt{d^2+h_1^2}}$$

$$B_2=\frac{\mu_0 I}{2\pi\sqrt{d^2+h_2^2}}$$

We divide the two magnetometer measurements:

$$\frac{B_1}{B_2}=\frac{d^2+h_2^2}{d^2+h_1^2}$$

We square both sides and solve for *d*

$$d=\sqrt{\frac{h_2^2-\left(\frac{B1}{B2}\right)^2 h_1^2}{\left(\frac{B1}{B2}\right)^2-1}}$$

This completes the derivation of the mathematical framework for determining the horizontal centerline, vertical depth, and current magnitude associated with electrically conductive underground deposits.

c) Analysis of Line Current Approximation

Biot–Savart's Law can be adapted to different conductor geometries. For example, in the case of a horizontal current sheet—such as a homogeneous, laterally extended conductive layer—the magnetic field is described simply as:

$$B=\frac{\mu_0}{2}J$$

where J is the surface current density in A/m.

However, such configurations are rare, as natural deposits of conductive material are seldom homogeneous. More often, deposits encountered in the field exhibit irregular geometry.

When the conductor has a more extended cross-section relative to the measurement depth, the Biot–Savart Law must be generalized to volumetric integration:

$$\boldsymbol{B}(r)=\frac{\mu_0}{4\pi}\int_V \frac{\boldsymbol{J}(r')\times(r-r')}{|r-r'|^3}dV'$$

In Denmark, the composition of underground strata has been heavily influenced by repeated glaciations, resulting in highly irregular and stochastic conductive features. These are typically shaped as long, narrow filaments, which supports the applicability of the line current approximation in most cases.

Figure 1: This photo shows the cross-section of an excavated ocher deposit filament. The white line represents 10 cm. The deposit was located 6 meters underground

When the aspect ratio $a/r \ll 1$ (where a is the conductor radius and r is the observation distance), higher-order terms in the field expansion decay rapidly and contribute negligibly. As a result, the magnetic field is primarily determined by the total current, and the conductor may be treated as an idealized line source.

a) Measurements in noisy environments

In electromagnetically noisy environments, it is advisable to phase-lock the magnetometer to the reference signal of the current being measured. This enhances measurement reliability by suppressing uncorrelated noise and harmonics.

b) Calculating total current exposure

Special consideration is required when summing the total stray current exposure in cases involving multiple subterranean conductive filaments.

While the source of the AC stray current may be identical, impedance discontinuities and variations in local conductivity frequently introduce phase differences between currents in separate filaments. At AC power frequencies (50 or 60 Hz), such phase differences can be substantial, leading to significant errors if current magnitudes are simply summed without correction.

To address this, each current should be treated as a phasor, where both magnitude and phase are encoded as a complex number. If the relative phase difference $\Delta\phi=\phi 2-\phi 1$, between two currents is known, the total current magnitude is given by:

$$I_{total}=\sqrt{I_1^2+I_2^2+2I_1I_2\cos(\Delta\phi)}$$

In practice, determining phase differences for 2–4 filaments is often manageable. However, accurately measuring the relative phase of 30 or more individual currents becomes technically challenging. In such cases, a simple arithmetic summation may be used to yield a conservative worst-case estimate, provided it is clearly described as such and not interpreted as an exact result.

5. Results & Discussion

a) **Case 1: Stray Current under a barn**

In this case study, a dairy cattle farm was adversely affected by ground-borne stray current.

A total of 29 distinct electrically conductive deposits were identified (se figure 2), and the magnitude of stray current associated with each deposit was individually estimated. Due to the large number of current-carrying anomalies, it was not technically feasible to measure the phase angles of all individual currents simultaneously. As a result, the exact total current could not be determined with certainty. However, a worst-case estimate—assuming all currents are in phase—yields a cumulative stray current of approximately 146 amperes.

Figure 2: Positional mapping of 29 separate electrically conductive deposits. The dairy cattle barn is located north of the area in the aerial photo. A few hundred meters to the

south of the photo there is a large electrical infrastructure complex, housing several systemic transformers.

Number	Depth (m)	Current (A)
1	3	5,4
2	5	3
3	4	5,4
4	6	9,3
5	3	1,6
6	7	4,9
7	5	3
8	5	8
9	8	4,4
10	6	3,9
11	5	7,5
12	7	8,4
13	4	2,8
14	3	2,5
15	6	5,4
16	8	5,2
17	3	2,4
18	7	5,9
19	4	2,2
20	8	4,4
21	3	2,25
22	2	1,1
23	7	5,6
24	9	12,6
25	2	2,4
26	2	2,1
27	5	3,75
28	9	6,7
29	8	13,6

Figure 3: Overview of the magnitude of the current propagated along the 29 different conductive deposits.

Given that the likely source of these currents is a large transformer station situated only a few hundred meters south of the affected area, this worst-case approximation may not be far from the actual value.

The adverse effects on the livestock were so severe that the farm owner eventually decided to shut down operations entirely due to concerns over animal welfare.

b) Case 2: Stray Current from a small transformer

In this case, a pig farm experienced stray current exposure originating from transformer imbalance at a nearby industrial site.

The total stray current measured at the transformer site was approximately 21 amperes.

This value was confirmed through direct measurements on the grounding cables, with results from the differential magnetometer method deviating by less than 10% from the directly measured values.

Figure 4: Verification measurements directly on one of the earthing cables from the transformer. Total calculated leak current from outside measurements was within 10% of the total current verified by direct measurement.

c) Case 3: Stray Current from a Wind Turbine

Several cases have been investigated in which farms were adversely affected by stray current emitted from wind turbines.

The proposed method, based on differential magnetic field measurements, has been successfully applied across multiple wind turbine sites, consistently yielding reproducible results.

Wind turbine foundations are often integrated into the grounding system, resulting in very low ground resistance—often in the range of 1–2 ohms. While this effectively dissipates fault currents, it can also lead to the propagation of significant stray currents through the surrounding soil and rock strata.

By mapping and quantifying the current transported through conductive underground deposits near the turbine base, the total amount of leaked current can be estimated.

To validate the external field measurements, magnetic field data were also collected near the array of bolts securing the turbine tower to its foundation. Although the bolts (approximately 2 cm in diameter and 25 cm in length) do not perfectly satisfy line current assumptions, they still provide a useful secondary dataset.

Figure 5: Low-impedance connection between generator mount and tower superstructure ensures that the wind turbine tower tube is fully utilized as a part of the grounding system for the wind turbine.

The results showed that current estimates based on bolt measurements were lower than those based on subsurface field measurements. The discrepancy is likely attributable to a secondary internal grounding system installed inside the tower structure.

In one representative case, stray current was observed along 211 distinct underground conductive filaments at a distance of 50 meters from the turbine base. The total worst-case (arithmetically summed) current leakage was nearly 200 amperes. In our investigations to date, no wind turbine has exhibited a total stray current leakage of less than 50 amperes.

These findings indicate that the magnitude of stray current emitted by wind turbines may reach levels that warrant serious consideration from an animal welfare standpoint.

d) Biological relevance

As noted in the introduction, the increasing number of legal compensations highlights the biological significance of stray current exposure, particularly in agricultural settings.

Several studies have linked current and magnetic field exposure to adverse health effects in both animals and humans (14, 15). One report correlates cancer incidence with contact currents as low as 18 µA (16), and observable behavioral effects in livestock have been reported at exposure levels as low as 0.5 mA (17).

Because every current produces a magnetic field, exposure to stray current necessarily implies exposure to alternating magnetic fields.

In some of the cases documented in this study, the magnetic field magnitudes associated with the stray current were well within ranges previously associated with biological effects in epidemiological studies.

For example, the risk of childhood leukemia has been shown to double at magnetic field exposure levels of 0.4 µT (18).

Figure 6: Measurement on one of the four separate grounding cables inside the wind turbine tower tube. The bolts are visible in the background.

Figure 7: Magnetic Field measurement directly on a stray current carrying ocher deposit filament. The measured value of 135uT and a distance of 5 centimeters correspond to a total current of 34 amperes.

One recorded field measurement on a stray current-carrying ocher deposit revealed a magnetic flux density of 136 µT at a distance of 5 cm, corresponding to a current of approximately 34 amperes (Figure 6).

Such field strengths may also interfere with human perception of natural electromagnetic phenomena, such as the Schumann resonances, which have been linked to neural oscillations (19, 20) and even blood pressure regulation (21).

Since the magnetic component of natural Schumann resonances rarely exceeds a few picoTesla, the presence of harmonic interference from 50 or 60 Hz stray currents warrants further investigation into potential bioelectromagnetic interactions.

6. Conclusion

This study has established a mathematical framework for estimating the magnitude of stray current propagated through electrically conductive filamentary deposits in the subsurface.

The proposed methodology is field-deployable and enables real-time or near-real-time assessment of stray current magnitudes.

This framework provides a valuable foundation for future investigations into the adverse biological effects of stray current exposure, which holds significance for animal welfare as well as human health.

7. Future Scope

As a potential future development, commercial production of instrumentation based on the measurement methodology presented in this study could prove highly valuable for veterinarians, farmers, and other professionals concerned with the health impacts of stray current exposure.

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Author Profile

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