TOPIC #6: FIELD COMPUTATION MODELS:

A: CALCULATIONS OF ELF ELECTRIC AND MAGNETIC FIELDS IN AIR

SYNOPSIS

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Characteristics of ELF Fields

The frequency of the power system is small enough that the electric and magnetic fields in air *can be considered as if they were independent* [1]. Further, the distribution of each field can be calculated under the assumption that static theory applies. Given this, both the electric and magnetic fields can be calculated from a scalar potential. With a knowledge of the conductors that make up the geometry and the distribution of surface potential and electric currents, the investigator can then calculate the electric and magnetic fields.

Consider next the differences in characteristics of the electric- and magnetic-field calculation problems.

Electric Field

Usually, the *potential on all power system conductor surfaces is reasonably well known*. Given this, the electric field can be calculated in a straightforward manner, using either one of two methods:

a) by direct solution of Laplace's equation for the potential and applying the gradient to obtain the electric field, or

b) by finding the electric charge and then calculating the electric field by superposition of the known electric fields from elementary distributions of charge.

The electric field at any point near the power system varies periodically at the power frequency. The rms value of this field is approximately constant in time because the voltages associated with the power system are approximately constant in time. Thus, it is possible to define a specific electric-field value associated with a point near the power system at all times.

The introduction of any dielectric or conducting material such as an animal or human subject generally *will cause large perturbations* in the electric field within and near the material. These perturbations depend upon the shape, orientation, and conductivity distribution of the material. [2]

This has serious implications for the exposure assessment problem, because the object of exposure assessment is often to calculate the fields and/or induced currents ($J = \sigma E$) within the subject.

Magnetic Field

The *distribution of current on power-system conductors is generally not well known*. Rather, the currents are very dependent upon power-system configuration and operating conditions. For example, on a given line the current can vary over a given day by a factor of more than four. Significant seasonal variation is also observed. These variations occur because of more or less predictable shifts in the demand for electric power, due to daily lifestyle patterns and seasonal weather changes. Another source of power-line current and magnetic- field variation is current unbalance that results in net currents.

For specified currents, however, the calculation of magnetic field can be done using superposition and a straightforward application of the Biot-Savart law. This law relates elementary distributions of currents to simple magnetic-field distributions. The difficulty of magnetic-field calculation is in relating the fields from specified currents to the real-time varying currents.

The introduction of any dielectric or conducting material such as an animal or human subject generally *will not cause* large perturbations in the magnetic field within and near the material. This dramatically simplifies the exposure assessment problem, because the object of exposure assessment is often to calculate the fields within the subject.

Magnetic materials, on the other hand, can cause perturbations in the magnetic fields. Fortunately, most subjects of exposure assessment are non-magnetic. Note, however, that the electric fields and/or induced currents generated by the time- varying magnetic fields depend upon the shape, orientation, and conductivity distribution of the subject.

Power-system Field Calculations

To illustrate how calculations can be done, consider one simple example for electric- and magnetic-field calculations. The example will be for an infinitely long single-conductor line.

Consider the geometry shown in Figure 6-1. Here, a single, infinitely long conductor at a potential $V = V_1$ and carrying a current I_1 is located at $(x,y) = (0,h)$ above an earth ($y < 0$). The (as yet) unknown line charge per unit length is ρ_l.

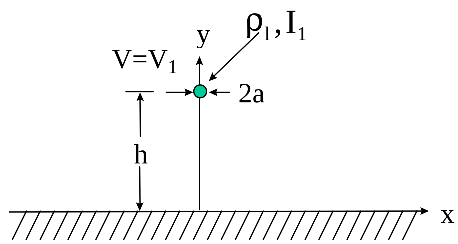

Figure 6-1. Cross-section of an Overhead Power Line Geometry

Electric Fields

The electric field will be calculated here using method b) from page 6A-1. For electric-field calculations, the earth can be assumed to be a perfect conductor and simple image theory used. Given this, the scalar potential and electric field for $y > 0$ can be written in terms of the (as yet) unknown charge per unit length as:

$$V(x,y) = \frac{\rho_l}{2\pi\varepsilon_o} \ln\left[\frac{(y+h)^2 + x^2}{(y-h)^2 + x^2}\right] \quad \text{volts} \quad (1)$$

$$\overline{E}(x,y) = \frac{-\rho_l}{4\pi\varepsilon_o}\left[\frac{2(y+h)\overline{u}_y + 2x\overline{u}_x}{(y+h)^2 + x^2} - \frac{2(y-h)\overline{u}_y + 2x\overline{u}_x}{(y-h)^2 + x^2}\right] \quad \text{volts / m} \quad (2)$$

where $\overline{u}_x$ and $\overline{u}_y$ are unit vectors in the x and y directions respectively.

To find ρ_l, set $V(0,h\text{-}a) = V_1$. The result is

$$\rho_l \cong \frac{2\pi\varepsilon_o V_1}{\ln(2h/a)}. \quad (3)$$

This value for ρ_l can be used in (1) and (2) to find the electric field for $y > 0$.

A similar procedure can be used to calculate the electric fields near three-dimensional structures with known potentials. The major difference is that finding the charge distribution is not as easy as the method shown above; it requires solution of a differential or integral equation. Recent work in this area is reviewed by Takuma and Kawamoto [3].

There are many situations (e.g., in substations, near electrical equipment and in residences) for which calculations are too complex to be practical. In these cases, systematic measurements may be preferred.

Magnetic Fields

Using the Biot-Savart law, the transverse magnetic fields of the single conductor at (x,y) = (0,h) carrying current I_1 can be written as

$$B_x(x,y) = -2I_1\left[\frac{(y-h)}{(y-h)^2 + x^2}\right] \text{ mG} \qquad (4)$$

$$B_y(x,y) = +2I_1\left[\frac{x}{(y-h)^2 + x^2}\right] \text{ mG} \qquad (5)$$

Here, the earth has been assumed to be transparent to magnetic fields. This is reasonable at power-system frequencies, because the earth is generally non-magnetic.

A similar procedure can be used to calculate the magnetic fields near three-dimensional structures with known currents. In this case, the procedure is not complicated by the need to calculate an intermediate unknown such as charge. Determination of the currents, however, may be difficult, especially if currents on unintentional conductors such as water pipes are important, as in the case of residences. A review of the problems of calculating magnetic fields near power systems is given in [4,5].

As mentioned under **Characteristics of ELF Fields**, the magnetic fields of a power system may vary considerably during the day and year; as a consequence, this field must be defined statistically. One reason why one must be careful with the definition of magnetic-field levels is that attempts to regulate magnetic fields are complicated by the question of how to define the magnetic field, at a point near a power line, by a single number [6].

Shielding

Electric Fields

Electric-field shielding is relatively easy to accomplish. Most conducting materials act as good electric-field shields at low frequencies. For example, a wood house will provide significant shielding from an external electric field. A good survey of work in this area is given in [5].

Magnetic Fields

Low-frequency magnetic fields are usually much more difficult to shield than electric fields. Rather than consider specific shields, a short discussion of several important parameters used to characterize the degree of shielding will be given. Good reviews can be found in [6,7]. The purpose here is to gain insight into the shielding process. The parameters of interest are discussed below.

Topology (Open vs. Closed Shields)
Shield topology is an important issue to be considered. "Closed" topologies are defined as shield geometries that completely divide space into "source" and "shielded" regions. "Open" topologies are defined as shield geometries that do not.

For closed topologies, the only mechanism by which magnetic fields appear in the shielded region is “penetration” through the shield. For open topologies “leakage” may also occur through seams or holes, or around the edges of the shield.

Material Type
It is possible to identify different shielding mechanisms with different material types. For example, when the magnetic properties (i.e., permeability) of a material dominate, shielding is by a mechanism called “flux shunting.” In this case, the magnetic flux from a source is diverted into the magnetic material and away from the region to be shielded. When the conducting properties (i.e., conductivity) of a material dominate, shielding is by a mechanism known as “eddy current cancellation.” In this case, currents are induced in the conductor by the magnetic fields of the source. These currents in turn cause magnetic fields that partially cancel those of the source.

Extent and Thickness of Shield
It is obvious that the extent of a shield can be an important factor when considering “open” shields. Generally, the more the shield geometry is like a closed topology, the better the shielding. However, if penetration exceeds leakage, increasing the extent of the shield may have little effect on the shielding.

The extent of a shield is also an important factor for “closed” shields. For example, it has been found that eddy-current cancellation works better for larger-diameter cylindrical or spherical shields, while flux-shunting works better for smaller-diameter cylindrical or spherical shields

If penetration is the dominant mechanism, a thicker shield will usually result in greater shielding. Even in this case, however, there will eventually be diminishing returns. This is due to the skin effect.

Frequency
No eddy currents are induced in a shield at zero frequency. Thus for frequencies low enough to ignore eddy currents, the flux-shunting mechanism dominates. Only shields with non-unity relative permeability will be effective in this case.

As the frequency increases, eddy-current induction becomes more important. Thus, “eddy current” shielding will generally be greater at higher frequencies.

Location and Orientation of Sources
The effectiveness of shields is known to be very dependent upon source location and orientation.

Gaps and Apertures
A shield is often constructed of several pieces. It can be shown that the electrical and/or magnetic continuity of the shield at junctions may have a significant impact on the effectiveness of the overall shield. The size of the gap need not be large for this to be the case. Further, wire connections at periodic locations along the shield may not be sufficient. Apertures cut in a shield may also influence shield performance. This will definitely be true if the aperture in the shield is oriented to cut the natural path of either magnetic flux or electric current in the shield.

Implications for Risk Assessment

Electric Field

The unperturbed electric-field calculations are quite accurate if the geometry and voltages of the sources are known.

In complex geometries, calculations are difficult and measurements may be preferable.

The rms value of the unperturbed electric field varies from point to point in space but not much with time.

The electric field inside a subject due to the unperturbed electric field is dependent upon the subjects' shape, orientation, conductivity distribution, and proximity to other objects.

Magnetic Field

For a <u>given</u> current and source geometry, calculations of unperturbed magnetic fields are quite accurate.

Determination of currents can be difficult, especially if currents on unintentional conductors such as water pipes are important.

The unperturbed magnetic field varies from point to point in space <u>and</u> with time because source currents generally vary with time. Thus, statistical calculations of magnetic fields are recommended.

The magnetic field within a subject is usually approximately equal to the unperturbed magnetic field.

The electric field inside a subject due to the time-varying unperturbed magnetic field is dependent upon the subject's shape, orientation, and conductivity distribution.

Remaining Questions

1. Which field is important? Is it the electric field, the magnetic field, or the current density?

2. Which *aspect* of the field is most important? Is it the peak value, the time-weighted average, the frequency content, the polarization, or something else?

3. For electric-field exposure calculations, can the effect of the subject's changing orientation and local environment be quantified?

4. There is not enough experience with the calculation of currents on complex systems of conductors. Is it realistic to do these calculations, or should measurements be relied on?

5. It is known that net currents can be an important parameter for calculation of magnetic fields. Can situations for which these are important be identified?

6. How can the statistics used to describe time variation of currents be used in calculations of magnetic-field statistics?

7. Magnetic-field shielding is known to be highly dependent upon source characteristics. In many cases, it is not easy to determine the sources. For these cases, can an easier way be found so that accurate shielding calculations can be done? If not, are there shielding schemes that are less dependent upon source geometry?

References

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