MAGNETIC FIELD MANAGEMENT

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INTRODUCTION

Because electrical apparatus is ubiquitous in our modern society and because of the nearly limitless ways that electrical energy is used in these devices, we live and work in an extremely complex electric and magnetic field environment. At low frequencies, the management of the electric and magnetic fields associated with the individual operation of these devices, with all of their attendant spatial and temporal complexities, falls into two comprehensive categories; cancellation and shielding.

Assuming that the on-going biological research will give electrical designers a set of parameters which should not be exceeded in the space near the device which humans will normally occupy, then on first blush, all needed techniques are available and well understood. Therefore, no new R&D would seem to be required and we should be able to redesign, rearrange, or retrofit to meet any emerging electric and magnetic field criteria. Unfortunately, understanding first principles is not sufficient to deliver a viable and practical product.

Before starting the discussion of the effort needed to get from first principles to effective products, it will be useful to review some very basic concepts associated with electric and magnetic fields. While the electromagnetic spectrum is a range of frequency from 0 cycles per second (Hz) to above 10^{20} Hz, the focus of attention of this document will be on the Extremely Low Frequency (ELF) band of 3 Hz to 3000 Hz. In the ELF band, electric and magnetic fields can be treated independently of each other.

Magnetic Fields

The amount of magnetic flux density, as referred to in this discussion, has historically been measured with a unit called the milligauss. However, electrical engineers and physicists have agreed on a different unit, the tesla, as an international standard. These terms have simple scaling relationships between them. One tesla is equal to 10,000 gauss or 10,000,000 milligauss. One tesla is, therefore, a very large field and as such is awkward to use when discussing typical fields found in our environment. In many cases, authors of technical journals frequently use the microtesla which is 1/1,000,000 of a tesla. However, in many older journals, and in most general public literature, the unit milligauss has been chosen when reporting environmental magnetic fields. These units may seem confusing. Therefore, conversion information, as presented below, has been developed to help the reader translate the material given in this text to that given in other presentations and publications. In all cases, the material presented in this discussion will use the milligauss unit and distance measured in feet.

Conversion Between Magnetic Flux Density Units

1 milligauss (mG) = 0.001 gauss (G) = 0.0000001 tesla (T)
1 milligauss (mG) = 0.1 microtesla = 100 Gamma

All magnetic fields are caused by moving electrical charge. In the general case, a moving charge is called an electrical current by engineers and physicists. The unit used to quantify the magnitude of the current is the "ampere". In an electrical circuit, the current in the wires, or conductors, of the circuit produces the magnetic field. In many discussions of fields, the magnetic flux density is used when values are reported. In free space and non-ferromagnetic material, the magnetic field and magnetic flux density are related by a simple constant called the permeability of free space.

All circuits which carry electric currents, from major power lines to the wiring and appliances in homes, produce magnetic fields. The strength of these fields depends on the geometry of the circuit, the amount of current in the conductors of the circuit, and the distance the observer is from the circuit. If the circuit is a single wire and very long relative to the distance to the observer, a very simple equation

$$\mathbf{B} = 6.56\ \mathbf{I}/\mathbf{r} \tag{1}$$

gives the magnetic flux density in milligauss. In this equation, **I** is the current in amperes in the wire and **r** is the distance from the wire to the observer measured in feet.

In more complex and typical cases, where more than one current is flowing and the circuit is not either long or simply a straight wire, a general form of an equation taken from classical physics, called the Biot- Savart Law, has to be employed to calculate these magnetic fields.

$$\Delta\mathbf{B} = \mathbf{k}\frac{\mathbf{I}\Delta \times \mathbf{r}}{\mathbf{r}^3} \tag{2}$$

where **k** is constant, **I** is the current in an elemental conductor section Δ, **r** is the distance vector from the elemental conductor section to the observation point, and r is the magnitude of the vector distance [1]. Equation (1) was produced by integrating Equation (2) over an infinite length of a straight wire. There are two other circuit conditions where simple approximations of the Biot-Savart Law have been developed which aid in estimation of magnetic fields. For a point distance from two long parallel wires carrying equal currents but in opposite directions, the following equation gives the magnetic flux density in milligauss

$$\mathbf{B} = 6.56\ \mathbf{Id}/\mathbf{r}^2 \tag{3}$$

where **d** is the distance of separation between the two wires and is much smaller than **r**. This equation is valid when the observer is at a distance from the set of wires. This particular equation is more useful because it is a helpful model to estimate the magnetic fields from conventional house wiring to transmission and distribution lines. In most house circuits, the current flows into the device through one wire and returns in the second. In modern house wiring, these two current carrying conductors are very close to each other; less than a quarter of an inch separation between the two conductors. For a house circuit carrying a maximum rated load of 20 amperes, just a foot from such a conductor, the fields would be approximately 2.7 milligauss. Moving to a point five feet from this circuit, the field would be only 0.11 milligauss. For this circuit configuration, as the equation shows, the magnetic field diminishes as the inverse square of the distance from the conductor. A similar inverse square relationship exists for transmission line fields.

If we go to the even more commonly considered source of magnetic fields, current flowing in a loop of wire, there is again a relatively simple equation that allows us to calculate the magnetic flux density in the plane of the loop when we are remote from the loop. That equation is

$$\mathbf{B} = \frac{\mathbf{10.31\,I \times a^2}}{\mathbf{r^3}} \qquad \mathbf{(4)}$$

where a is the radius of the loop given in feet. A common example of currents flowing in a coil or wire is the burner on an electric range. For large 8-inch diameter burners with a 3-inch diameter open center and five concentric loops drawing 5 amperes of current, the magnetic flux density would be approximately 14.3 milligauss at one foot from the center and yet only 0.11 milligauss five feet from the burner. In all cases, fields from conductor loops decay very rapidly as you move away from the coil. The equation indicates that the field will diminish as the inverse cube of the distance. In fact, it can be shown that in all regions remote from a current loop, not just in the plane of the loop, the magnetic field decays with the cube of the distance. Therefore, when you move away from a loop of current, the field diminishes rapidly if the dimension of the loop is small relative to the observer's distance from the loop.

These three simplified relationships all stem from applying the Biot-Savart Law to the circuit geometry. The Biot-Savart equation is derived from the Ampere Law, which is one of the group of equations known as Maxwell's Equations for electromagnetic systems. A first principle of the magnetic field resulting from current in a conductor element is that the magnetic field varies inversely with the square of the distance from the conductor element. The changes in direction of the current and therefore the vector relationship of the magnetic field result in cancellation or addition of the magnetic field contributions from other field elements. By combining the fundamental l/r relationship with the mathematical description of the physical configuration of the circuit, the apparent change in exponential decay of field with distance are shown. These equations with different orders of decay, however are, in reality, the result of cancellation or addition effects.

Electric Fields

The electric field intensity, or simply electric field, results from the separation of charge. The usual letter symbol used in technical literature to denote the electric field is "E". In the context of this discussion, energized conductors are the usual source of charge. The unit of measure applied to electric field is Volts/meter or V/m. This is the international standard and also the generally used term in public discussions. However, when discussing electric fields found near very high potential sources such as extra high voltage transmission lines, the prefix "k" for kilo (1000) is generally used so that the unit is expressed in kV/m or 1000 V/m. Some scientific journals report field in Volts/centimeter or V/cm which is 100 V/m.

In many contexts, electric fields are more difficult to quantify than magnetic fields. Basic physics shows that not only are electric fields derived from charge separation but that force is always exerted on these charges.[1] If the charge exists in a medium which permits the charge to move, the medium is considered conductive and the electric field will adjust in magnitude and direction with the movement of the charge. Nearly everything in our environment is conductive and therefore impacts electric fields. At 60 Hz, air has a conductivity of less than 10^{-9} siemens. Metals have conductivities of greater than 10^{7} siemens. The human body has a mid-range conductivity of 1.5 to 0.01 siemens.[2]

The fact that nearly every physical object will distort the electric field makes the control technology very easy. Placing any grounded metallic surface between the electric field source and the subject will, as a practical matter, eliminate the electric field since the conductivity difference between air and metals is greater than 10^{16}, the metals will transport the terminating charge to the metal surface. At ELF frequencies, the metal surface can be as simple and inexpensive as 2 inch mesh chicken wire screen. The shielding efficiencies are greater than 10^4 (see Figure 1).

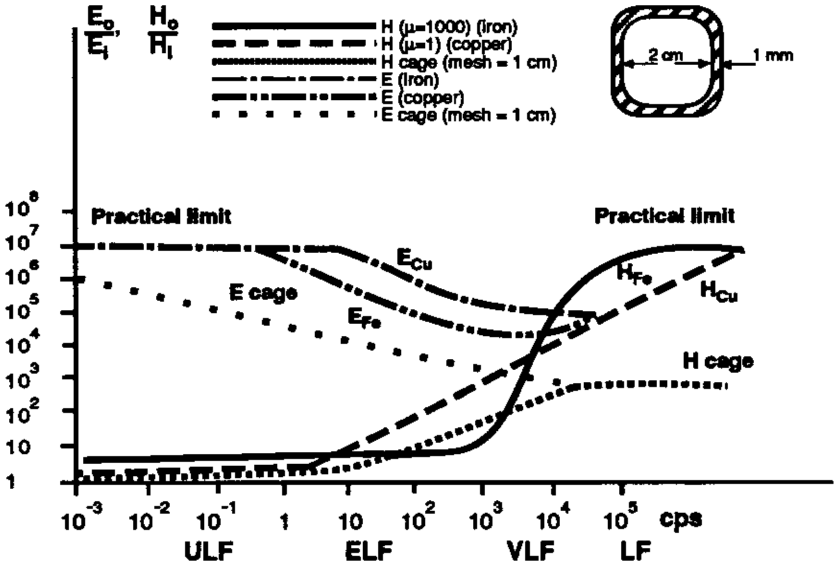


Figure 1. Practical shield factors for electric (Eo/Ei) and magnetic (Ho/Hi). Components at low frequencies for a special box or cage made of copper or steel (r=100 cm; d-0.1 cm; mesh distance 1 cm). The practical limit in respect to theory is due to idealization in the theory (Homogeniety, Smooth Surfaces, Perfect Joints A.S.O.)

Cancellation techniques also work for electric field management. Two conductors carrying charge to and from an electrical device, if placed close together, will effectively cancel the electric field from each individual wire at a remote site. However, for tools and plug-in appliances, a switch-off device may actually have larger electric fields than a switched-on device. This apparent paradox results from the switch breaking only one of the conductor circuits. If the plug is not polarized, there is a 50% chance that the break is in the ground circuit. Therefore the device "floats" to full line potential and an electric field is set up between the device and local grounds. A very common example of this effect is an electric blanket. Of course, for this simple example the fix is simple; just use a two pole switch, *if the application does not violate local code.*

While cancellation techniques work and in some cases are the only practical management technique for electric field control, shielding is usually much easier to apply. The subject can be shielded, such as in the extreme of live-line-maintenance personnel who work on energized extra high voltage conductor systems, or the device can be shielded such as placing a metal shroud around a pad-mount transformer. Since electric field shielding is generally applied as a direct consequence of maintaining electrical safety in the work environment, it is not likely that an extensive effort would be required to further manage electric fields. Therefore, the remainder of this paper will focus on the much more difficult problem of magnetic field management.

CANCELLATION CONSIDERATIONS

Achieving field management or control of magnetic fields below a certain level which may be demanded by the on-going biological research may require a technique with a tremendous dynamic range. For example, in electric power transmission, it has long been recognized that the attenuation of magnetic fields remote from a transmission line relies on the cancellation technique. The phase currents in a given conductor are effectively opposed by the current(s) flowing in the opposite conductor(s), either for single-phase systems or balanced multi-phase systems. Therefore, at distances remote relative to the spacing between the conductors, the magnetic field of one conductor is nearly canceled by the opposite fields created by the current in the other conductor(s). Should the requirement be to reduce magnetic fields at the edges of right-of- ways from 100s of milligauss to tens of milligauss; circuit techniques that have long been understood involving phase positioning in double circuit lines can achieve this cancellation effect. In fact, research at the EPRI-HVTRC facility has shown that a single-circuit transmission line can be constructed to have these same characteristics.[3] However, if the range of reduction required is not by one order of magnitude but by greater than two orders of magnitude, then other much more subtle phenomena must be accommodated. While most transmission line phase currents are nearly balanced, they are in fact always in some state of unbalance. That state of unbalance results in current return paths other than the intended three-phase conductors. This unbalance current return path will generally be through the earth's mantle. Wagner and Evans show that this equivalent depth of return is given by the equation

$$D_e = 2160/f \qquad (5)$$

where D_e is in feet.[4] Under normal earth resistivities (=0.01 s) and with transmission lines of lengths from terminal to terminal much greater than the return depth, the effective return path for the unbalance (zero sequence 60 Hz) currents will be at depths of 2800 feet. Third harmonic currents would return at 1600 feet. Such effective return paths for the unbalanced current indicate that cancellation by $1/d^2$ relationship only occurs at great distances from the conductor system. Thus the complication is not the theory of how cancellation works, but is the reality of how electrical systems actually operate and how a system must be designed to operate.

The above example points out the need to examine each field management problem for basic electro-magnetic characteristics before selecting the magnetic field management strategy. Thus, this paper will not attempt to solve problems of controlling magnetic fields of specific devices or apparatus. It will discuss the general nature of magnetic field control problems associated with a variety of electrical apparatus classes.

While transmission and distribution lines are highly focused on by the public, little emphasis will be placed upon electric power transmission and distribution systems. The Electric Power Research Institute

(EPRI), the DOE, and the utility industry are spending considerable effort in evaluating the possible options for reducing magnetic fields associated with both transmission and distribution circuits. The article in Reference [3] gives an excellent discussion of the R&D underway and required to manage power delivery related magnetic fields. Therefore, little effort should be required by NIOSH on power distribution external to buildings.

The principal focus should be on the general category of electrical apparatus found in work sites that have considerable capability for producing magnetic fields. While the general public may not have extensive exposure to any one of these devices, specific classes of workers will find themselves consistently exposed.

Cancellation fields can be set up in some cases with very little cost penalty. In many cases, a principal source of magnetic fields is found to be that which radiates from the conductor systems leading to the tool or power apparatus. In such relatively simple cases, these fields could be canceled via compaction of the conductor systems. For example, a low voltage device, either a 120 or 240 volt service, is typically supplied by a power cord and the fields any distance from the cord are rapidly attenuated by the d^2 relationship. In the situation where the cords or leads have to be very close to the worker, then the added precaution of twisting or interleaving of these leads with each other will further reduce the field. The net effect of twisting a pair of conductors is that each individual conductor appears to occupy the same space. Therefore, the fields are much more effectively canceled because the spacing between the conductors is reduced to nearly zero.

Examples of where this has already been practiced are recent attempts by waterbed manufacturers and electric blanket manufacturers to significantly reduce the magnetic fields produced without impairing the ability of the device to generate heat as required to perform its function. This simple additional step makes it possible to produce devices that have very low magnetic field characteristics and not experience significant cost increase.

Attempting to have the power leads twisted or superimposed with each other relies on the ability of the conductor insulation system to withstand the added electrical stress. Even for the low voltage circuits, compaction must be carefully considered because eventually the insulation could be compromised and create a shock hazard. *Therefore, in exercising magnetic field control technologies, it is extremely important that long established practices for maintaining safety of the device must not be compromised.*

Electrical apparatus that consume considerable energy would generally be supplied by three-phase sources. Compaction may require the use of three- phase cables rather than single-phase cables. If single-phase cables are used, care in bundling of the cables within cable trays and the routing of the cable trays can be a very effective control technology. In many instances where strong fields have been found near transformer vaults in buildings, the source of magnetic field is the cable systems leading to and from the transformer vault.

The magnetic field produced directly from most apparatus exhibits the characteristics of loop current source fields. Therefore, a simple control technique may be to move the device, i.e. a compressor motor in a refrigeration unit, to the back of the unit's housing. This makes use of separation distance and, therefore, the $1/d^3$ characteristic. If the device function does not permit it to be moved, i.e., hand held tools, then more sophisticated and possibly expensive techniques must be employed.

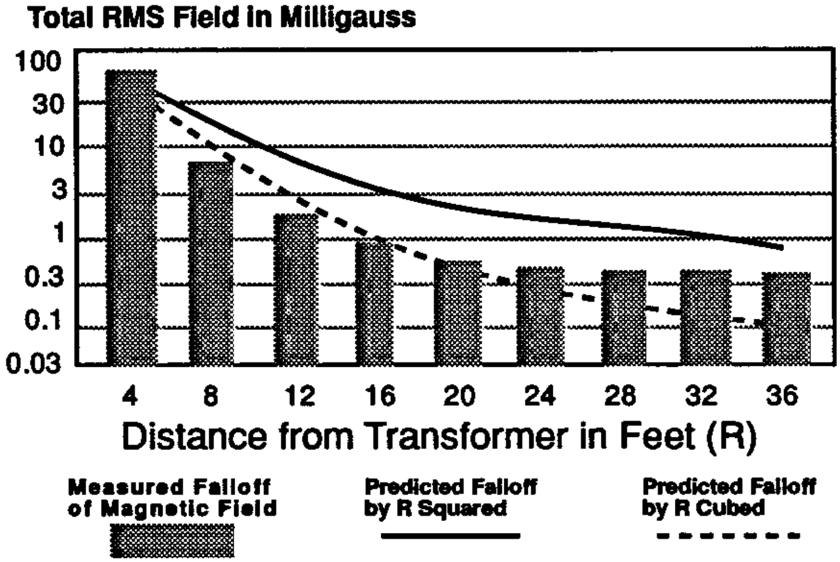
SHIELDING CONSIDERATIONS

Shielding of ELF magnetic fields requires either that: the magnetic fields be diverted around the volume considered to be sensitive to the magnetic fields, or the magnetic fields be contained within the device that produces the fields. Effectively accomplishing shielding at either the source or the subject requires extreme care in choosing the shielding material. The electrical properties of ferromagnetic materials are very complex functions of magnetic field frequencies and magnitudes. For strong magnetic fields, the highly non-linear saturation characteristics of ferromagnetic materials have been widely recognized and reasonably adjusted to achieve source shielding. However, only a few engineers and physicists are aware of the effects of coerciveness at very low magnetizing forces. Subject shielding invariability involves weak magnetic fields. Ferromagnetic materials that are normally considered to have very high permeability may have quite low permeability if being used to attempt to shield milligauss field levels. Thus, the problem of dynamic range encountered when trying to apply cancellation techniques reappears in a different form when attempting to utilize shielding techniques.

In the simplest terms, transformers operating at any power level could be considered devices which offer source shielding. Of course, operation of the transformer is dependent on the control of the flux paths so that the maximum flux linkage between the primary and secondary windings of the transformer is obtained. This control of the flux path is, however, the same as shielding in that the flux is steered or diverted from its normal free-space radiating pattern. Close inspection of the transformer magnetic circuit will reveal that there is still considerable leakage flux in a complex pattern about the coils and the transformer steel. This stray flux or leakage flux from the transformer (whose magnetic circuits are intentionally operated at magnetic flux densities of 11,000 to 14, 000 gauss) would appear to be a strong source of magnetic field even if only a very small percentage is leakage field. However, the electrical conductor paths in a transformer are loops or coils and as shown in the discussion above, at any significant distance (relative to the coil radius) the magnetic field falls off as the cube of distance. Figure 2 shows the results of actual measurements on a 300 kVA pad-mount transformer which supplies a small electronics firm.

When shielding is attempted with ferromagnetic circuits in low field regions, i.e., not the high intensity fields associated with the operation of transformers, motors, or other magnetomotive force devices, the permeability level of the ferromagnetic material may be drastically reduced. The ability of the ferromagnetic material in terms of shunting or shielding is highly dependent on the level of the flux

Figure 2. Lateral Profile of Magnetic Fields from a 300 kVA Pad-Mounted Transformer

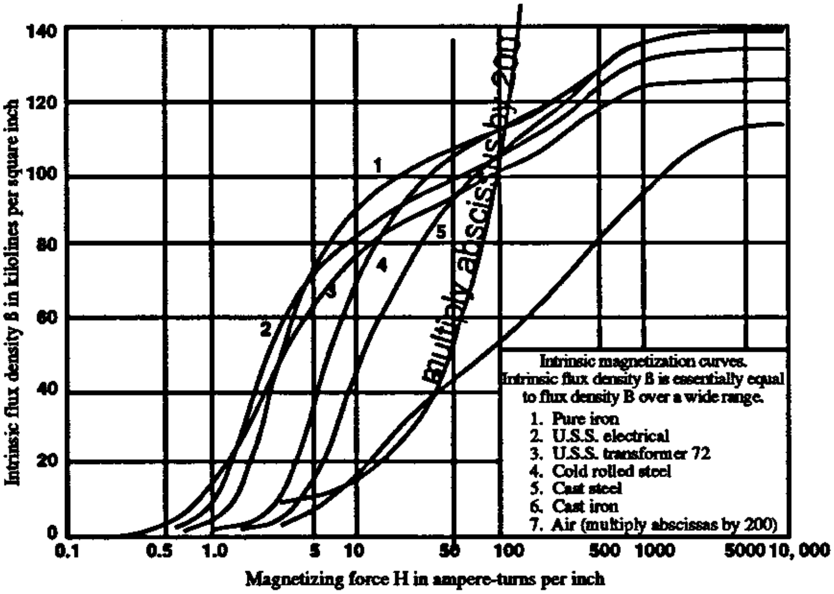


density to be shunted. While it is difficult to find this phenomena discussed with any significant detail in modern literature, Figure 3 from Reference [5] clearly demonstrates this basic characteristic of ferromagnetic metal was documented 60 years ago. Reference 1 merely states that the "initial relative permeability" of iron is 200.

Since magnetic field levels which are being investigated as possible levels of concern are in the order of tens of milligauss, it will be a significant problem to try to shield workers or the public from remote source magnetic fields with local ferromagnetic shielding devices. In fact as Figure 1 from Reference [6] shows, the best shielding from ELF magnetic fields may actually be achieved by non-ferromagnetic high conductive copper rather than by "high mu metal" materials. High mu metal materials have low conductivity, and as shown, for very weak fields, do not have high relative permeability. Copper has a relative permeability of 1, but copper is very conductive and the eddy currents that are set up by the weak magnetic fields in the copper sheet act as cancellation fields. Therefore, copper may be as effective if not more so than the ferromagnetic material. Unfortunately, neither of these are very effective, i.e., the shielding efficiencies are less than 10.

There is a further shielding problem associated with developing shielding devices remote from the magnetic field source. The shield region is actually a very small part of the overall magnetic circuit and, therefore, has very little impact on diverting magnetic fields once the magnetic fields' distance from the device starts to equal the dimension of the device. That is, the reduction in reluctance to the magnetic field's circuit path is minuscule and will have little or no effect on diverting of fields. Therefore, if for instance shielding were attempted along one wall of an office facing a distribution circuit, the shielding would only slightly reduce the field if the person stood directly next to the shield, even if a high permeability could be achieved. When the person moves half the dimension of the wall height away from the wall, the shielding would be trivial.

Figure 3. BH Curves of a Variety of Iron and Steel Products with the Region of Very Low Flux Density Shown.



Based on Wagner and Evans (4)

A further engineering consideration for any control technology using subject shielding is that these techniques would be inordinately expensive. To date, to be effective and practical, shielding is best when applied at the source of the magnetic field. This simple statement is not that easy to achieve because of the tremendous number of devices which exist that produce at least locally high magnetic fields. Achieving redesigns of these devices to manage and control these fields could be extremely expensive and therefore cost prohibitive in many situations. Retrofit to control these magnetic fields would essentially be out of the question in most cases.

There are companies that specialize in developing shielding devices for magnetic field sensitive products such as VDTs. Since reducing the field by an order of magnitude or less may be sufficient to reduce a magnetic field which had been producing visual distortion of the screen, such shielding is effective. However, in terms of getting orders of magnitude reduction, there are really no devices that are seriously proposed for remote shielding that can be utilized.

CONCLUSIONS

Magnetic field management will generally be much more complex than electric field management. While cancellation and shielding are control techniques that can be applied to either electric or magnetic fields, shielding is much more effective for electric fields. The appropriate control technology to apply will depend on: the magnitude of the field to be managed, the percentage of reduction desired, the dominant field being electric or magnetic, the physical characteristics of the source, the function of the source, and the function of the worker relative to the source.

Taking specific steps to managing a particular field environment may not be appropriate until field levels and characteristics (e.g. power frequency levels, degree of polarization, harmonic content, dB/dt transients, 60 Hz level changes, frequencies above ELF concurrent with power frequency levels, etc.) can be set by on-going scientific investigations.

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