TOPIC 13: FIELD-MANAGEMENT TECHNOLOGIES

SYNOPSIS

Prepared by
Gary B. Johnson
Power Research Engineering
Adams, MA

Introduction

Field management minimizes the impact that magnetic or electric fields have on their surroundings. It may be necessary to reduce electric- or magnetic-field interference or to allay public or employee concern. The management of magnetic or electric fields may involve the following:

- educational and measurement programs
- prudent avoidance
- site arrangement
- design change
- cancellation
- shielding

or a combination of these methods.

A variety of field-management techniques has been developed so that they are available for use should they be needed to reduce fields [1,2,3,4,5,6,7,8,9]. Management of electric fields, when required, is usually accomplished through material shielding or source rearrangement. Examples of electric-field shielding techniques are conductive suits used by transmission live-line workers and conductor rearrangement or compaction of power lines. Power-line phase arrangement or compaction can be used to reduce electric fields, although corona effects such as audible noise, radio noise, and corona loss may increase. Grids of wires, grounded metal-covered walkways, or appropriately placed trees may also be used to reduce electric fields and associated electric shocks that may be due to the electric fields. Electric-field shielding techniques are discussed in Reference 9. Management of magnetic fields can be more difficult because they are not effectively shielded by many materials. This synopsis will focus on magnetic-field management.

Magnetic-field Management Technology

Figure 13-1 provides insight to several field-management strategies. It provides the magnetic-field equations for four different wire configurations. The first is a single current-carrying wire.

The second is an example of lines carrying equal but opposite currents, such as the wiring in a residence. The third example has the current in one of the conductors split and positioned on either side of the other conductor. The fourth wiring example is a current loop similar to the current flow that might be found in many common appliances.

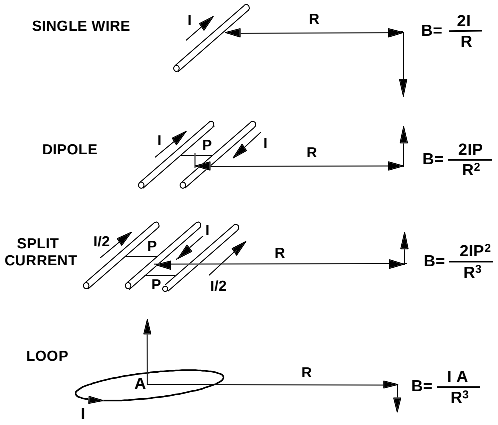

Figure 13-1. Magnetic-field equations for four different wire configurations. I is in Amperes; A is in square meters; R is in meters; and B is in milligauss.

Five methods of field management can be derived from observation of Figure 13-1.

- Increase distance ***(R)*** from the conductors.
- Match the current ***(I)*** in a conductor with an opposing current in a nearby conductor.
- Decrease the distance ***(P)*** between the conductors or the area ***(A)*** of the loop.
- Split the current ***(I)*** of one conductor and position around the other conductor.
- Decrease the current ***(I)***.

A sixth field-management option is to reduce the field in selected areas (shielding) by use of conducting materials that cancel the field through induced eddy currents, or by flux-shunting materials that redirect the magnetic field. Essentially all field-management strategies make use of one or more of these techniques.

Distance

Distance from magnetic-field sources can be obtained by rearranging a site, such as an office or room in a home, so that areas with higher magnetic fields are less frequented. In some cases, the magnetic-field sources can be relocated to increase the distance.

Current Reductions

The magnetic field can be reduced by decreasing the current in a source. For transmission and distribution lines, one method to reduce the current is to increase the voltage. This will decrease the current for the same amount of power transfer *(Power = Voltage x Current = 2 Voltage x ½*

Current). While this may be a viable option for new power lines, it would require extensive changes for existing lines and transformers. Similarly, this option might be possible for new buildings (if equipment and appliances were readily available at the higher voltage), but would require extensive changes in wiring, outlets, or transformers for existing buildings.

Ideally, the net current (vector sum of currents) on a set of conductors is zero; however, this is not always the case where there are multiple grounding paths in the power distribution system, as illustrated in Figure 13-2. Current may return to a transformer through both the service neutral and multiple neighborhood grounding paths [10,11]. Overall improvement of the power-system neutral and its connections, dielectric couplers in the water system, or Net Current Control Devices on service conductors (Figure 13-3) [12,13] can reduce stray grounding current and the resulting magnetic fields.

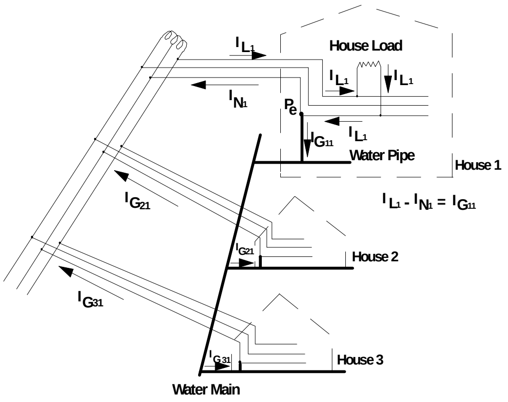

Figure 13-2. Multiple grounding paths in a neighborhood.

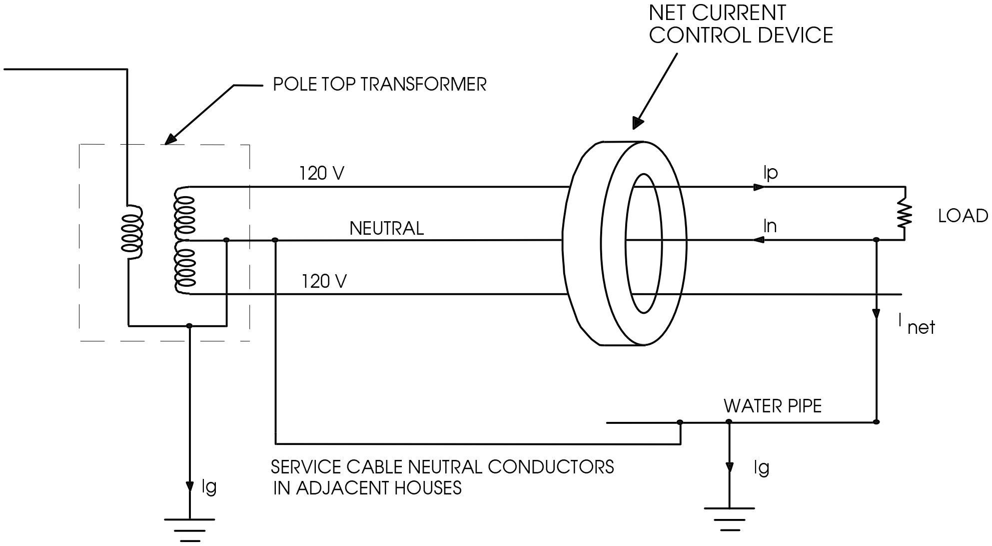

Figure 13-3. Net Current Control device inductively couples the neutral and voltage conductors together, *encouraging* current to return on the neutral instead of on alternative ground paths.

Currents can be reduced by improving the power efficiency of devices. Devices at higher operating voltages will also decrease their current use for the same power usage.

Design Changes

Design changes can reduce the magnetic field of sources. This is usually accomplished by decreasing the distance between conductors—for instance, decreasing the loop size in appliances to provide better cancellation of the currents. Figure 13-4 provides an example of this for an electric-range element [14].

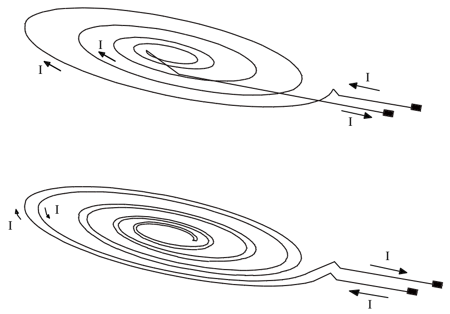

Figure 13-4. Example of a low-field electric range element compared to a typical electric-range element. In the low-field range element, the current returns along the same path, minimizing the current loop size.

Reducing the phase spacing of power lines, known as compaction, can lower their magnetic fields. Figure 13-5 illustrates the midspan compaction of an existing line using interphase insulators [15]. Not only is the phase spacing of the line reduced, but also the ground clearance of the two outer phases is increased. The use of interphase spacers may not be appropriate for all lines due to concerns with structural loading, line tensioning, or corona performance.

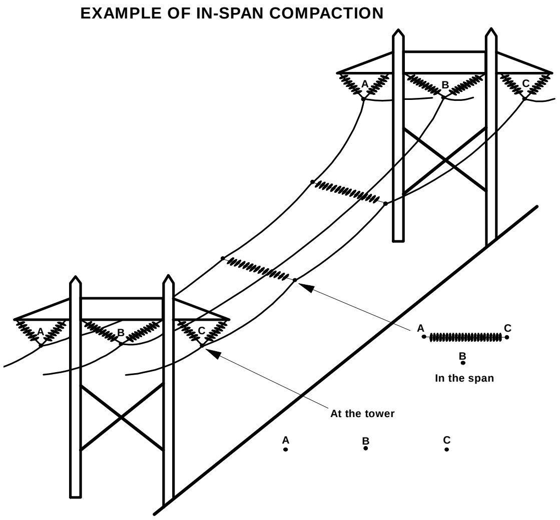

Figure 13-5. Midspan compaction of an existing line using interphase-insulators without line structure changes.

Other power-line design changes that can reduce the magnetic field include phase arrangement on multiple-line corridors and phase splitting. The current phasing of multiple power lines on the same tower or corridor can be arranged to provide some cancellation of the currents and thus lower fields.

Phase currents of power lines can also be split and placed, as illustrated in Figure 13-6 for two split-phase line designs to further reduce the magnetic field [15]. This provides even better cancellation of the currents than for a compact line, so that the magnetic fields decrease with the cube of the distance instead of just the square of the distance. Figure 13-7 compares the magnetic-field profile of a compact vertical split-phase 115-kV line to the field profile of a conventional 115-kV line with a flat configuration.

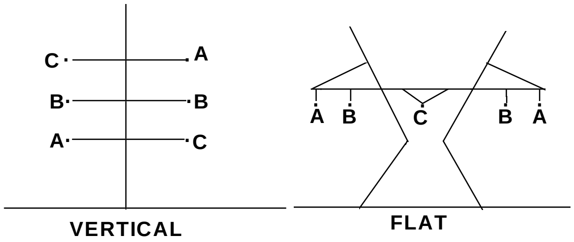

Figure 13-6. Two split-phase line designs.

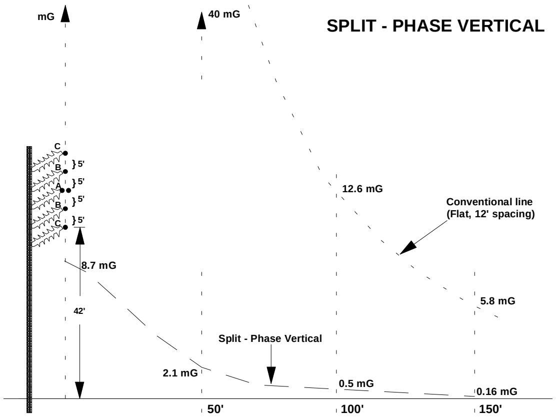

Figure 13-7. Example of a compact vertical 115-kV low-field split-phase line. The magnetic-field profile is compared to the magnetic-field profile of a conventional flat 115-kV line with a 12-ft. phase spacing.

Compaction and phase-current splitting are effective only when the line has essentially no net current and the currents are well-balanced. This is usually the case for higher-voltage transmission lines, but it is not necessarily true for distribution lines and for some lower-voltage transmission lines [16]. Low-field line design options such as compaction and phase-splitting are discussed in several references [1,2,7,8,15]. Compaction can provide field reductions of a factor of 2 or 3, while phase-current splitting can provide field reductions by a factor of 10, depending on location.

Even greater field-reduction factors are possible for compacted and split-phase lines designs [2] through extreme compaction of the line design. Extreme compaction is possible if the line conductor motion is limited through the use of interphase spacers, very short span lengths, or very high line tensioning. The conductor motion must be limited in order to maintain sufficient conductor separation to adequately prevent line flashovers; however, other line-design factors such as insulation strength, conductor vibration, or maintenance access may then become the limiting factor.

Any change in power-line design will affect the line impedance, corona performance, mechanical behavior, flashover, and total system performance. These factors must also be considered when evaluating line design changes for magnetic-field management.

Field Cancellation with Current Loops

Loops of current can be placed to reduce or cancel the magnetic field in specific areas such as rooms with equipment sensitive to interference from magnetic fields. The current in the loops can be either actively driven (active loops) or passively induced by existing fields (passive loops). A discussion of field cancellation with loops is provided in Reference 3.

Active Loops

Active loops generally have a magnetic-field sensing coil located in the field of interest. The signal from the sensing coil provides feedback to control the amount of current driven in the loop. [17]. The active loop is located such that its magnetic field reduces or cancels the existing magnetic field.

Active loops can consist of multiple-turn coils with small conductors, because the current is actively driven in the loops. The actively driven current can also contain harmonics of the power frequency, if necessary, to reduce or cancel harmonics in the existing magnetic field. An active loop can be a multiple-frequency device, but it does require external power. Active loops can essentially cancel the magnetic field at specific locations, but will increase the field at other locations.

Passive Loops

Like active loops, passive loops are oriented so that their field will reduce the existing magnetic field. Current is induced in passive loops, however, by the existing field. Passive loops usually consist of single large conductors to minimize impedance. A series capacitor is often placed in the loop to help cancel the loop’s inductive reactance, thus lowering the loop’s overall impedance. Since the loop current is passively induced, low overall impedance of the loop is critical.

Passive loops are self-regulating, coupled directly to the external field, and require no external power. Passive loops are optimized for peak field-cancellation performance at a specific frequency (usually the power frequency) [18,19]. They are essentially single-frequency devices. If harmonics are present, multiple loops tuned to specific harmonic frequencies are required.

Passive loops can often be designed to reduce the magnetic field in an area by factors of 3 to 8, but will increase fields in other areas.

Material Shielding

Field management can also be achieved through use of material shielding. Material shielding of ac magnetic fields uses either conductive material or ferromagnetic material. To be more effective, material shields should enclose either the magnetic-field source or the area to be shielded, as illustrated in Figure 13-8. Connections between sections of shielding material should be securely joined by soldering or welding [6,20].

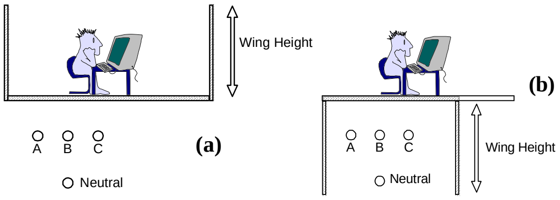

Figure13-8. To minimize *fringing* of the magnetic field around the edges of the shield, the material shield should essentially enclose either *(a)* the area to be shielded or *(b)* the field source. This can be accomplished by extending the shield material up past the area to be shielded or down past the field source.

Conductive Material (flux cancellation)

Conductive material acts as a shield because induced eddy currents produce a magnetic field that opposes the existing magnetic field. A conductive sheet is similar to an infinite number of microscopic passive loops. The field perpendicular to the conductive sheet induces the eddy currents. Thus, a conductive sheet is most effective in shielding magnetic fields perpendicular to its surface. It has little effect on fields parallel to its surface [1,6,21,22].

Ferromagnetic Material (flux-shunting)

Ferromagnetic material shields by redirecting the magnetic field. Ferromagnetic materials, such as iron or steel, shunt the magnetic flux past an area, essentially providing a short cut between two points, or short circuit, for the magnetic field. It is most effective shunting flux that is parallel to its surface; it has little effect on the magnetic field perpendicular to its surface. An effective flux-shunting material is one with a high permeability. Iron and steel have high permeabilities, but some alloys—such as mu-metal, a mix of nickel, iron, copper and chromium—have even higher permeabilities. These alloys have higher permeabilities than just iron or steel but are more expensive and can be difficult to handle [6,21]; however, they can be quite effective for shielding small regions (PC monitors).

Combination of Materials

Some materials provide both flux-shunting and conductive-eddy current shielding. Iron and steel are both flux-shunting and conductive materials. They can provide flux-shunting at DC and low frequencies and conductive-eddy current shielding at higher frequencies. The geometry of source and shield interacts with these materials in a complex way. Changing the source - shield distance may produce poorer shielding at low frequencies, but better shielding at higher frequencies. An effective method of providing both conductive and flux-shunting shielding is to use layered conductive and high-permeability materials, such as an aluminum-steel sandwich. An aluminum-steel sandwich can often provide better shielding than a single material layer of similar thickness [1,6,20,23].

Aluminum or steel plates can reduce magnetic fields by factors of 5 or 10 in many situations. Special materials, such as mu-metal, can reduce fields by even larger factors in certain situations.

Field Management Situations

RAPID Engineering Project #8 considered six distinct sources of magnetic fields. They are as follows:

- transmission lines
- distribution lines
- substations
- building wiring
- appliances
- transportation systems.

Each source presented a unique set of limitations and possibilities for field-management options. The effectiveness, cost, environmental impact, and safety concerns of the field-management options were considered for each of the six source situations [1].

Transmission Lines

Magnetic-field management techniques of line compaction, phase-splitting, voltage upgrading, underground pipe-type cables, and passive cancellation loops were evaluated. A 500-kV or 765-kV option could not be identified to meet 50- to 100-mG field levels on the right-of-way. A passive loop might be an effective method to keep the field levels below 50 mG at the edge of the right-of-way. Costs for a 345-kV line could triple or quadruple to meet a 20-mG level on the right-of-way, and increase by as much as 50% for 230-kV lines and 20% for 69-kV to 115-kV lines. Underground pipe-type cables would likely be needed to reach a 2-mG level near the lines, but they are not commercially available for voltages exceeding 345 kV [1]. Outside the right-of-way, magnetic fields could be kept below 5 mG for most new 69-kV to 230-kV lines for an approximately 25% to 50% increase in cost using compaction and split-phase designs [7].

Distribution Lines

Magnetic-field management techniques of line compaction, phase-splitting, voltage upgrading, and net-current control were evaluated for balanced phase - current conditions. For balanced current conditions, significant cost increases were seen only when field levels of 5 mG or less in the right-of-way were used. Costs increased up to 40% for 13.2-kV line designs, and 50% or more for 34.5-kV lines, in order to reach a 2-mG level in the right-of-way. Heavily loaded distribution circuits would likely require underground conduit to reach a 2-mG level in areas near the line.

For *balanced current* power lines, the use of spacer cable (small distance, <1', between insulated conductors) would reduce the fields in nearby residences to below 2 mG. However, unbalanced current (zero sequence current) conditions on distribution lines are common [24]. If 2-5-mG levels were set as targets, control of zero sequence current (net current) would be necessary. This would require changes in distribution-voltage selection, grounding methods, line design, and transformer sizing [1].

Substations

Most of the magnetic field at a substation perimeter is due to transmission and distribution lines entering and existing. Costs and limitations would be similar to those listed for transmission and distribution lines. A low-field substation might require an expansion of the perimeter fence. Methods for reducing the fields in the substations encountered by workers include shielding of metal-clad switchgear and gas-insulated buses [1].

Building Wiring

A variety of resident/utility customer-owned power-distribution equipment exists: for instance, transformers, switchgear, buses, service panels, and general wiring. Grounding beyond the service panel can be a significant field source if alternate return-current paths are created.

For new buildings, magnetic fields in frequently occupied areas can likely be minimized through careful planning and positioning of equipment with little or no additional cost. The magnetic fields due to transformers, buswork, and feeders pose a more difficult problem to manage, if necessary.

Field management includes wiring to avoid or correct stray return-current loops, installation of net-current control devices (Figure 13-3), use of metal conduit, and material shielding of buses, feeders, and transformer vaults. A 2-mG to 5-mG target level in all areas could increase the installation cost of vaults, buses, and feeders by 50 to 100%.

Magnetic-field management in existing buildings will be more difficult than for new construction. Wiring changes and material shielding will likely be required with costs dependent on the target magnetic-field level and situation. Some office buildings have already had to retrofit with magnetic-field shielding to reduce computer-display interference [1].

Appliances

The primary sources of magnetic fields in end-user devices are resistive heating elements, motors, transformers, power cords, and general wiring. Field-management options for these include use of adjacent return (Figure 13-4) or bifiliar heating elements, replacement of inexpensive motors with more expensive heavier-duty motors, use of torodial transformers, compaction of wiring, and installation of shielding for most sources. Some industrial-welding and electrically heated metal-melting processes would present extraordinary costs and design challenges to meet low-field limits [1].

Transportation Systems

Power and low-frequency magnetic-field limits would affect electric transportation systems such as railways. Field limits within the transportation right-of-way would be difficult to meet, given the design of the system. Field-management techniques might include dual overhead bus-type feed systems, use of higher voltages, and shielding [1].

Summary

A variety of field-management strategies has been developed for use if needed. Some of these management techniques for magnetic field have been used to reduce interference with equipment, such as PC monitors, or to allay public or employee concern. Field management can be accomplished through separation, source modification, or shielding with loops or material. The cost of field management depends strongly on the magnetic-field source and the target field criteria. Field management becomes much more costly and complex when source modification or material shielding become necessary. Electric-field management, when necessary, can usually be accomplished with conductive material shielding.

Key Questions

1. How cost-effective are various field-management options in reducing population exposure to magnetic fields?
2. How could field-management techniques be applied to obtain the best field reduction for the most people?
3. How should field management, engineering, and cost assessments be evaluated for new lines versus retrofit of existing lines ***or*** total line application versus local site applications?
4. What inconveniences and lifestyle changes will the various field-management options impose?
5. What field-management options will society accept?
6. Are there collateral benefits provided from field-management options*? Possible examples would be: more efficient appliances from reducing currents; smaller appliances due to compact wiring; smaller transmission-line right-of-way resulting from compact lines; stronger buildings and less space between floors due to more steel and less concrete.*
7. Are there increased risks (downsides, such as safety issues) to the field-management options?

References

1. Johnson, T.R., Gauger, J.R., Evaluation of Field Reduction Technologies, RAPID Engineering Project #8, IIT Research Institute for Oak Ridge National Laboratory EMF Research Program, US Department of Energy, 1997.

2. EPRI, Magnetic Field Management for Overhead Power Lines: Potential Options for Low Field Designs, EPRI Report TR-104413, Electric Power Research Institute, Palo Alto, CA, September 1995.

3. EPRI, Magnetic Field Management for Overhead Power Lines: Field Reduction Using Cancellation Loops, EPRI Report TR-105571, Electric Power Research Institute, Palo Alto, CA, December 1995.

4. EPRI, Handbook for the Assessment and Management of Magnetic Fields Caused by Distribution Lines, EPRI Report TR-106003, Electric Power Research Institute, Palo Alto, CA, December 1995.

5. EPRI, Transmission Cable Magnetic Field Management, EPRI Report TR-102003, Electric Power Research Institute, Palo Alto, CA, 1993.

6. EPRI, Material Based Magnetic Field Shielding Design Guide, EPRI Report TR-109271, Electric Power Research Institute, Palo Alto, CA, 1997.

7. Electric Transmission Research Needs Task Force, Electric and Magnetic Field Reduction: Research Needs, State of Washington, Department of Health, Olympia Washington, January 1992.

8. Rodick, S., Musser, P., “Evaluation of Measures and Costs to Mitigate Magnetic Fields from Transmission and Distribution Lines”, Proceedings of the 1993 Missouri Valley Electric Association Engineering Conference, Kansas City, MO, 1993.

9. EPRI, Transmission Line Reference Book - 345 kV and Above: 2nd Edition, Electric Power Research Institute, Palo Alto, CA, 1982.

10. Mader, D., Zaffanella, L., “Network Analysis of Ground Currents in a Residential Distribution System,” IEEE Transactions on Power Delivery, PWRD-8, 1993.

11. EPRI, Network Analysis of Ground Currents in a Residential Distribution System, EPRI Report EL-7369, Electric Power Research Institute, Palo Alto, CA, August 1991.

12. EPRI, *“Net Current Control Device,”* Power System Magnetic Field Management Seminar, Tab 10, EPRI High Voltage Transmission Research Center, Lenox, Massachusetts, September 1994.

13. Hoffman, H., Preston, G., "Reduction of Stray Currents and Magnetic Fields from Single-Phase Power Distribution Systems," IEEE Transactions on Power Delivery, PWRD-10, No. 2, April 1995.

14. Johnson, G.B., "Magnetic Field Sources in Residences: Measurement, Detection, and Options", EMF Management Techniques Training Session: 1994 IEEE/PES Transmission and Distribution Conference and Exposition, Chicago, Illinois, April 14, 1994.

15. Johnson, G.B., Clairmont, B.A., "Low Field Transmission Lines: Design Concepts," Proceedings of the 1995 CIGRE Study Committee 36 Colloquium, Foz do Aquacu, Brazil, May 1995.

16. Olsen, R.G., James, D.C., Chartier, V.L., "The Performance of Reduced Magnetic Field Power Lines Theory and Measurements on an Operating Line," IEEE Transactions on Power Delivery, PWRD-8, 1993.

17. Johnson, U. Larsson A., Sjodin, J, "Optimized Reduction of the Magnetic Field Near Swedish 400kV Lines by Advanced Control of Shield Wire Currents: Test Results and Economic Evaluation," IEEE Transactions on Power Delivery, PWRD-9, No. 2, April 1994.

18. Walling, R, Paserba, J, Burns, C, "Series-Capacitor Compensated Scheme for Enhanced Mitigation of Transmission Line Magnetic Fields," IEEE Transactions on Power Delivery, PWRD-7, 1992.

19. Clairmont, B.A., Fardanesh, B., Hopkins, L. Shperling, B., Zelingher, S., "Passive Shielding Loops for a Multiple Line Corridor," Proceedings of the 1995 CIGRE Study Committee 36 Colloquium, Foz do Aquacu, Brazil, May 1995.

20. EPRI, Material Shielding of Power Frequency Magnetic Fields, EPRI Report TR-109550, EPRI, Palo Alto, CA, 1998 (In-Press).

21. EPRI, Handbook of Shielding Principles for Power System Magnetic Fields, EPRI Report TR-103630, Electric Power Research Institute, Palo Alto, CA, April 1994.

22. Lim, K.C., Hoburg, J.F., Fugate, D.W., Lordan, R.J., "Integral Law Descriptions of Quasistatic Magnetic Field Shielding by Thin Conducting Plates," IEEE Transactions on Power Delivery, PWRD-12, No. 4, October 1997, pp. 1642-1650.

23. Hoburg, J.F., Clairmont, B.A., Fugate, D.W., Lordan, R. J., "Comparisons of Measured and Calculated Power Frequency Magnetic Shielding by Multilayered Cylinders," IEEE Transactions on Power Delivery, PWRD-12, No. 4, October 1997.

24. EPRI, *Survey of Residential Magnetic Field Sources*, EPRI Report TR-102759, Electric Power Research Institute, Palo Alto, CA, 1993.