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Transmission Line Electromagnetic Fields
Risk, Assessment and Reduction

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TRANSMISSION LINE ELECTROMAGNETIC FIELDS

RISK, ASSESSMENT AND REDUCTION

By

Khadija Ben Kilani

A THESIS

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ABSTRACT

TRANSMISSION LINE ELECTROMAGNETIC FIELDS
RISK, ASSESSMENT AND REDUCTION

By

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Power frequency electromagnetic field (EMF) exposures are essentially inevitable in modern society, and their possible association with health hazards is unclear and controversial. Magnetic fields present a methodological obstacle for epidemiologic studies and exposure assessment. Scientific research in the area has not verified mechanisms by which low intensity EMF interacts with the human body, and thus setting guidelines for magnetic field assessment is difficult. Overhead transmission lines represent a long term exposure to low frequency magnetic fields for organisms within the right-of-way. Thus, as a precautionary measure, controlling the magnetic fields of overhead transmission lines should be evaluated. The geometrical line configuration of transmission lines is a critical factor in minimizing the magnetic field intensity at the right-of-way. The conductor height and phase arrangement are two main geometrical measures. Two case studies of transmission systems are presented to illustrate magnetic field reduction. Various other techniques for magnetic field minimization are described.

To my parents Azzouz and Fatma Ben kilani,
my sisters Saloua, Najoua, Raoudha and Lamia,
and my brothers Lasaad and Mohsen
for their love and support

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CHAPTER ONE

INTRODUCTION

AND
BACKGROUND

Although electric and magnetic field effects of overhead ac transmission lines are but a part of the overall characteristics of electric energy systems, their relative importance has grown due to recent greater use of higher voltage lines, which has increased since 1970.

The ac transmission system in the United States developed from a need to transfer large blocks of energy from remote generation facilities to load centers. The transmission and generation of electric energy has come long way from the 500 volts transmission line which emanated from the Great Barrington, Massachussetts' plant in 1886 (1). Through the years, generating stations have multiplied and increased in capacity. They have gone from a 2000 kW generator in the first modern steam electric station, to larger than 1,000 MW in a single unit.

Based on Edison Electric Institute (EEI) reports, the peak noncoincident electric load in the United States is shown in Figure 1

for the period 1920-1978 (2). The peak load increased from 8600 to 344,000 MW between 1920 and 1973, or at an annual rate of 7%. During the years 1973 to 1978, the annual rate decreased to 3.5% as a consequence of fuel cost, availability and conservation efforts.

The peak load, although now growing at a smaller rate, will continue to require expansion of utility transmission systems.The circuit miles of ac overhead transmission lines in service at the end of 1977 and through 1986 for the total electric utility industry in the United States are shown in Figure 2. The data is taken from reports by the Edison Electric Institute and the National Electrical Manufacturers Association (NEMA) (2). Note the increase of higher voltage lines, with higher loading capabilities.

Along with the electric utilities requirements for higher capacities, more distribution circuits, pipelines, railroads and highway systems are gradually invading the land. This has resulted in competition for land and rights-of-way and an increased public perception of the danger of high-voltage or high-current wires to people and vegetation.

ORIGIN OF ENVIRONMENTAL IMPACT EVALUATION:

During the late 1960's, the general public began to react to the growth of transmission systems. Public concern was heightened in the latter 1960's by the environmental movement, which promoted the passage of the National Environmental Protection Act (NEPA) of 1969 (1).

NEPA has since made environmental values a concern of every federal

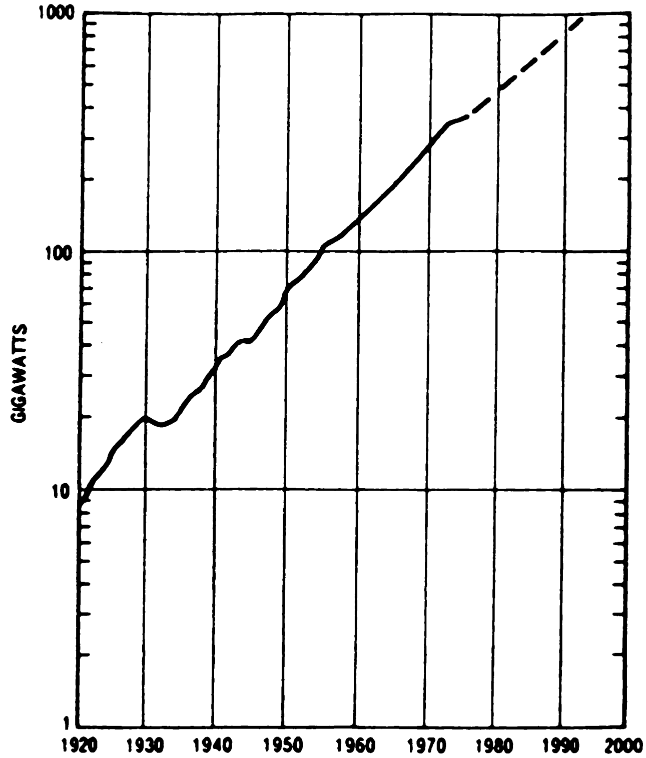


***Figure1**. Peak electric load growth of utilities in the United States from 1920 until the year 2000. The dashed portion of the curve is only an estimation of the load growth. (from EEI)*

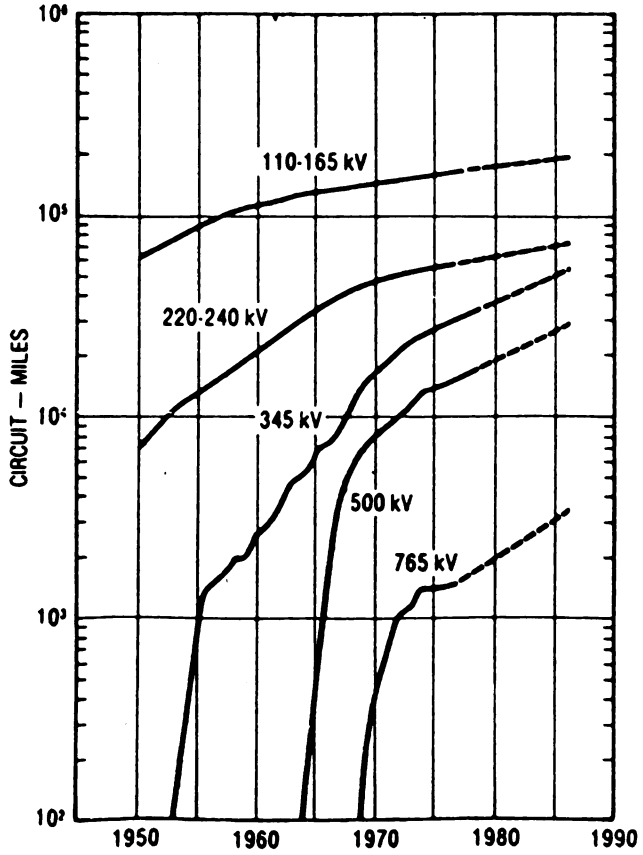


Figure 2. Circuit miles of overhead AC transmission lines in the United States. (from EEI and NEMA)

agency. These federal agencies set the pattern by developing environmental impact guidelines, which were then followed and modified by state regulatory agencies to suit the need of their state. The state procedure usually results in the issuance of a certificate of need or license, to construct and operate a facility given certain environmental guidelines. Under such procedures, a proposed transmission facility is usually evaluated according to:

(1) The impact on present and future land use plans
(2) The construction and maintenance impact on the local and regional environment
(3) Psychological and social impacts on the local populace
(4) The transmission impact of any particular transmission construction project on local communities
(5) The need for the facility and its financial impact on the utility and its rate of structures
(6) The operating effects of the energized lines, including but not limited to electric and magnetic field effects

The last issue consists of assessing potential hazards to the public of the operation of any particular transmission line.

Since 1960, the effects of electric and magnetic fields on the human body and vegetation have been studied. Although, as a response to the growth of higher-voltage transmission lines, emphasis in these early studies was on the effects of electric fields, especially those nearby high-voltage transmission lines. A significant number of

studies with humans, animals and plants, found electric fields from power lines to be harmless.

At the same time, low-voltage distribution lines, frequently encountered in residential areas were generally assumed to be harmless. This held until 1979, when Wertheimer and Leeper (6) reported that children dying of cancer reside more in homes with “low-voltage high-current configuration “ than control children.

High-current carrying distribution wires are generally at or near the substations, where the voltages are stepped down. In modern power delivery systems, high-voltage wires carrying current at voltage up to several hundred kilovolts (kV) deliver power to distribution substations, where the voltage is stepped down. This results in a higher current in the medium voltage (usually 13 kV line-line) primary lines. These latter distribute power from the substation through a neighborhood. At the local or service transformer, the voltage is stepped down to produce 240 volts, which is carried along secondary wires, to service drops which reach the customer’s service entrance. The current flow is greatest in the wires directly coming from the substation or the service transformer. Higher current lines result when the voltage is stepped down.

First, note that at power frequencies, electric fields are caused by voltages between conductors and ground and are always present when the system is working. However, magnetic fields are fields created by the current flowing in the wires and are present only with load. Magnetic fields penetrate the human body and buildings readily, and they are not easily shielded. We use EMF as a generic term to represent both electric and magnetic fields.

Although long-term biological and neurological studies to determine the effects of magnetic field on humans, animals and other forms of life is still continuing, public concern about magnetic field exposure hazards has stimulated new measurements and techniques to reduce or possibly eliminate these fields. Florida is the only state that currently has effectively put a magnetic field exposure limit on transmission lines. It is set at 200 mG. Several research projects are investigating techniques to reduce magnetic field strength along the edges of the right-of-way (ROW) of the transmission or distribution circuits.

To aid in evaluating this research, we would like to answer the following questions:

. What is the role of the line configuration in controlling the magnetic field along the edges of the right-of-way?

. What are some possible modifications in the line geometry that will reduce the magnetic field along the ROW?

. What are the difficulties of magnetic field exposure assessment?

First, in order to indentify the phenomena, a summary of the main epidemiological studies on possible health effects of exposure to EMF is presented in chapter two. Emphasis will be on cancer studies and childhood leukemia. Chapter three characterizes the various sources of human exposure to EMF and instrumentation needed for magnetic field exposure assessment.

Chapters four and five bring together the theory and calculations regarding the phenomena of magnetic fields associated with ac transmission lines. A brief description of some magnetic field

concepts related to power lines is given in chapter four, while necessary calculations are in chapter five. Some computer simulation for magnetic and electric field calculation prorgrams are also described.

To give a clear picture of a common transmission line circuit, a description as well as some typical line configurations are presented in chapter six.

Chapter seven deals with the possible techniques and line configurations for magnetic field reduction at the edges of the ROW.

The cases proposed are presented in chapter eight. First, some typical line configurations found in residential areas are investigated. Second, some modifications are applied to the original circuit to minimize the magnetic field intensity at the edges of the ROW.

In chapter nine, the proposed solutions for the different cases are evaluated and their feasibility is discussed, to make a final conclusion.

CHAPTER TWO

HEALTH EFFECTS OF ELECTROMAGNETIC FIELD EXPOSURE EPIDEMIOLOGICAL STUDIES

INTRODUCTION:

The biologic and health effects of electric and magnetic fields have been a public concern since 1960. Emphasis has been on the effects of the electric fields, particularly those nearby high voltage transmission lines. A significant number of studies with humans, animals and plants found no evidence of effects that could be considered harmful to human health.

In several post-1979 epidemiologic studies of childhood cancer, interest shifted from electric fields to the magnetic fields associated with high current wiring, encountered in proximity to homes or work locations.

Epide.niology is a science of association, relying on statistics to detect connections between harmful agents and patterns of disease in human population. Based on this science, at least 20 (4) epidemiologic studies have been conducted in the magnetic field effect area, trying to find evidence of correlation between lines

carrying high current loads and health effects. Among the health consequences of exposure to magnetic fields, three concerns have been addressed by epidemiologists: cancer, reproduction and neuropsychological effects. Of these three, the cancer studies attracted the greatest amount of public attention. In this chapter, a review of the main studies and their results is presented. These results are often expressed in terms of risk ratios, odds ratio and confidence intervals which are defined below. Note that results must be evaluated considering "confounders" which are alternate causes of the disease under study. Results should also be viewed from the perspective that exposure to magnetic fields in the urban population, has changed little since ac urban electrification began early in this century. As commercial, industrial and residential loads increased, transmission voltages increased and distribution wiring spacing have decreased, resulting in less magnetic fields in many instances.

Odds Ratio (OR):

An odds ratio is a measure of the increased risk of a certain health effect, compared to the normal or the background rate (5). For instance, if the normal occurrence rate was one case per 20,000 per year, an odds ratio of 2.0 implies an increase to two cases per 20,000 per year.

Confidence Interval (CI):

An interval for a parameter, constructed from a particular set of data in a way designed to assure that it covers the actual value of the parameter with a very high probability. It ranges from the lower bound to the highest conceivable value of the parameter(5). The parameter in this case is the magnetic field measurement in milligauss. For instance, a 2.0 mG value measurement with a 95% confidence interval implies that the actual value is confined in the interval [1.975,2.025] mG, with a probability of 0.95.

Relative Risk:

The magnitude of a risk expressed as its ratio to a reference risk. In this case, it is the ratio of the number of cancer cases among groups exposed to stronger fields to the number of cases among groups exposed to weaker fields. A relative risk of one means "no change in the cancer incidence rate".

Risk Ratio(RR):

The ratio of risk between two categories of populations, especially in the sense of relative risk. In this case the two categories would be the population under study and the control population.

I - CANCER STUDIES:

The first time cancer was associated to EMF was in 1979, when Wertheimer and Leeper (6) compared the home environments of children with cancer and a control population in an attempt to detect any statistical correlation between home environments and the occurrence of cancer. Their study was not based on direct measurement of the magnetic field strength in the homes. Rather, a wire coding of the configuration of the utility wiring nearby the subject's homes was assigned. The study cut down the configurations into two wire codes: Low Current Configuration (LCC), and High Current Configuration(HCC). Their study results imply an odds ratios between 2.0 and 3.0, which indicates that children dying from cancer

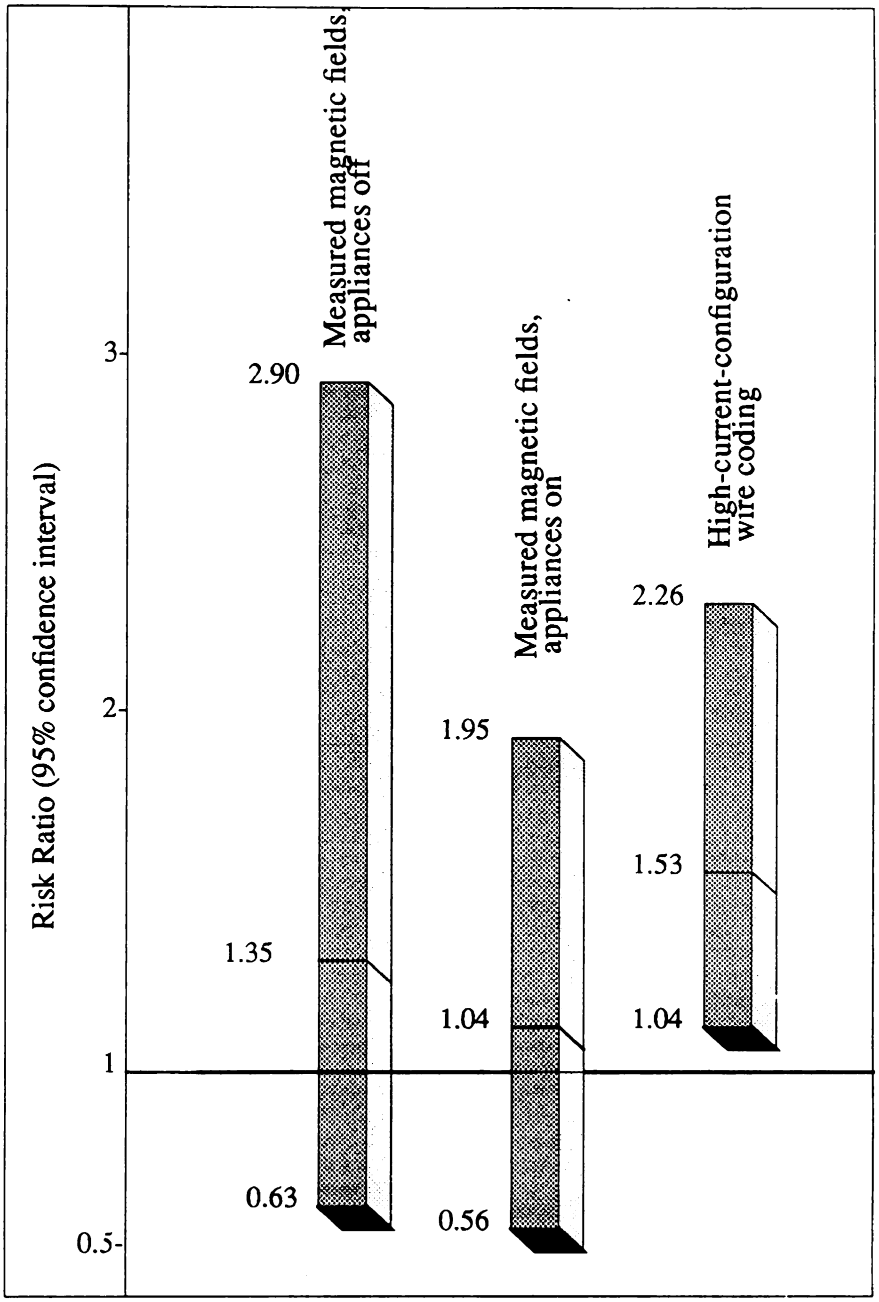
reside more often in homes with a nearby high current configuration (HCC) than do children from the control population.

The publication of their work created widespread scientific discussion of their methods and their results. Their wire coding was criticized of being an inaccurate substitute for actual field measurement. In 1988, the Savits, et. al. study(7) was an expansion of Wertheimer and Leeper's study, with an improved procedure.The wire coding used was the same, whereas point in time measurements of the magnetic fields in the subjects homes were recorded. Although their study found a statistical correlation between cancer and the high current configuration (HCC) coded homes, the correlation between cancer and increasing magnetic field magnitudes measured was insignificant.

In fact, considering that the confidence interval (CI) is 95% (Figure 3), (8) the margin of error suggests that there may be no correlation between cancer and the measured fields. A confounder such as economic status is likely involved in the configuration coding.

Since 1982, broader knowledge about the issue was gained and can be summarized under the following study titles:

- Leukemia case control studies.
- Brain cancer control studies.
- Cohort studies of electrical workers.
- Skin melanoma case control studies
- Welding and exposure to EMF.
- Male breast cancer.



SAVITZ'S RESULTS

Figure 3. *The vertical axis shows the ratio of the number of cancer cases among children exposed to stronger magnetic fields to the number of cases among children exposed to weaker fields. The vertical bands represent the statistical uncertainty that results from the relatively small number of people in each case. (ref 7)*

1.1 Leukemia case control studies:

Since 1985, about five case control studies on leukemia among workers occupationally exposed to EMF have been published. Table 1 (4) presents a summary of the corresponding results. One can observe large numbers of leukemia cases and high odd ratios, higher than those observed in the exploratory studies. Although all of the five studies seem to strengthen the possible association between leukemia and working in an 'Electrical occupation', they suffer from the lack of an accepted and verifiable exposure assessment procedure and investigation of confounders. The latter is important since most electrical occupations have many chemical exposures.

1.2 Brain cancer control studies:

The second cancer site of the most concern to epidemiologists, is the brain. Seven studies of brain cancer and occupational exposure to EMF have been published since 1985 [Table 2] (4). Reports have shown significant numbers of brain cancer cases among workers exposed to electromagnetic fields. Elevated odd ratios were statistically significant, and dose-response relationships were observed more than once. The results are not consistent as Speer (4) reported an odd ratio of 13.0 among utility employees of Texas, while Pearce (4) reported an odds ratio of only 1.01 for all electrical workers in New Zealand. Both studies were estimated based on occupational history obtained from questionnaire and registration forms.

Table 1. Results of five case control studies on leukemia among electric workers occupationallyexposed to EMF. (ref 6)

	case / control	exposure assessment		OR
Gilman 1985	underground coal miners	time spent underground	all L	2.53 (40)
	140 leukemia deaths		acute L	2.85 (22)
	160 non cancer deaths		chronic L	8.22 (14)
			CLL	6.33 (11)
			myelogenous L	4.74 (17)
			AML	3.80 (14)
Stern 1986	naval shipyard workers	job histories + years employment	for electricians	
	53 leukemia deaths		all L	3.00 (1.29- 6.98)
	212 members of cohort		ML	2.33 (0.77- 7.06)
	alive at dx of cases		LL	6.00 (1.47-24.45)
			for welders	
			all L	2.25 (0.92- 5.53)
			ML	3.83 (1.28-11.46)
			LL	0 (----)
Flodin 1986	population based search for association with gamma rad in houses	postal questionnaire	for electrical workers (elec. technicians, elec. welders, computer telephone mechanics)	
	59 AML alive		AML 3.8 (1.5 - 9.6)	
	345 general population controls			

Table 1 cont'd

	case / control	exposure assessment	OR	
Coggon 1986	male cancers in 3 UK counties 29 acute myeloid leukemia 2913 other cancers	occupational history through postak questionnaires	AML a cluster of 5 electrical workers in these 29 cases	
Pearce 1989	New Zealand cancer reg. 80 - 84 534 male leukemia all other cancers	occupation on registry forms	for all electrical workers	
			all L	1.62 (1.04- 2.52)
			acute L	1.25 (0.62- 2.54)
			chronic L	2.12 (1.19- 3.76)
			ML	1.22 (0.60- 2.48)
			LL	1.73 (0.89- 3.37)
			AML	1.16 (0.48- 2.84)

Table 2. *Results of seven case control studies on brain cancer and occupational exposure to EMF. (ref 6)*

	case / control	exposure assessment		OR
Lin 1985	Maryland residents 519 glioma/astrocytoma deaths 519 random non cancer deaths	occupation on death certificates panel rating based on occupations	EMF exposure determined from occupation	
			A (definite)	2.15 (1.1-4.1)
			B (probable)	1.85 (0.9-3.9)
			C (possible)	1.44 (1.1-2.0)
			D (no)	1.00 - - - -
Coggon 1986	male cancer in 3 UK counties 97 brain cancers 2845 other cancers	occupational history through postal quesxtionnaires	electrical engineers	1.9 (0.4-5.6)
			electrical and electronics workers	2.0 (0.8-4.1)
Thomas 1987	Louisiana, N. Jersey, Pennsylvania residents 435 brain cancer deaths 386 non-brain cancer deaths	occupational history from next of kin panel rating based on occupations	MW / RF radiation	1.6 (1.0-2.4)
			MW / RF manufacture repair of electric equipment	2.3 (1.3 4.2)
			electronic workers	3.9 (1.6-9.9)
			Dose - response relationship	

Table 2 cont'd

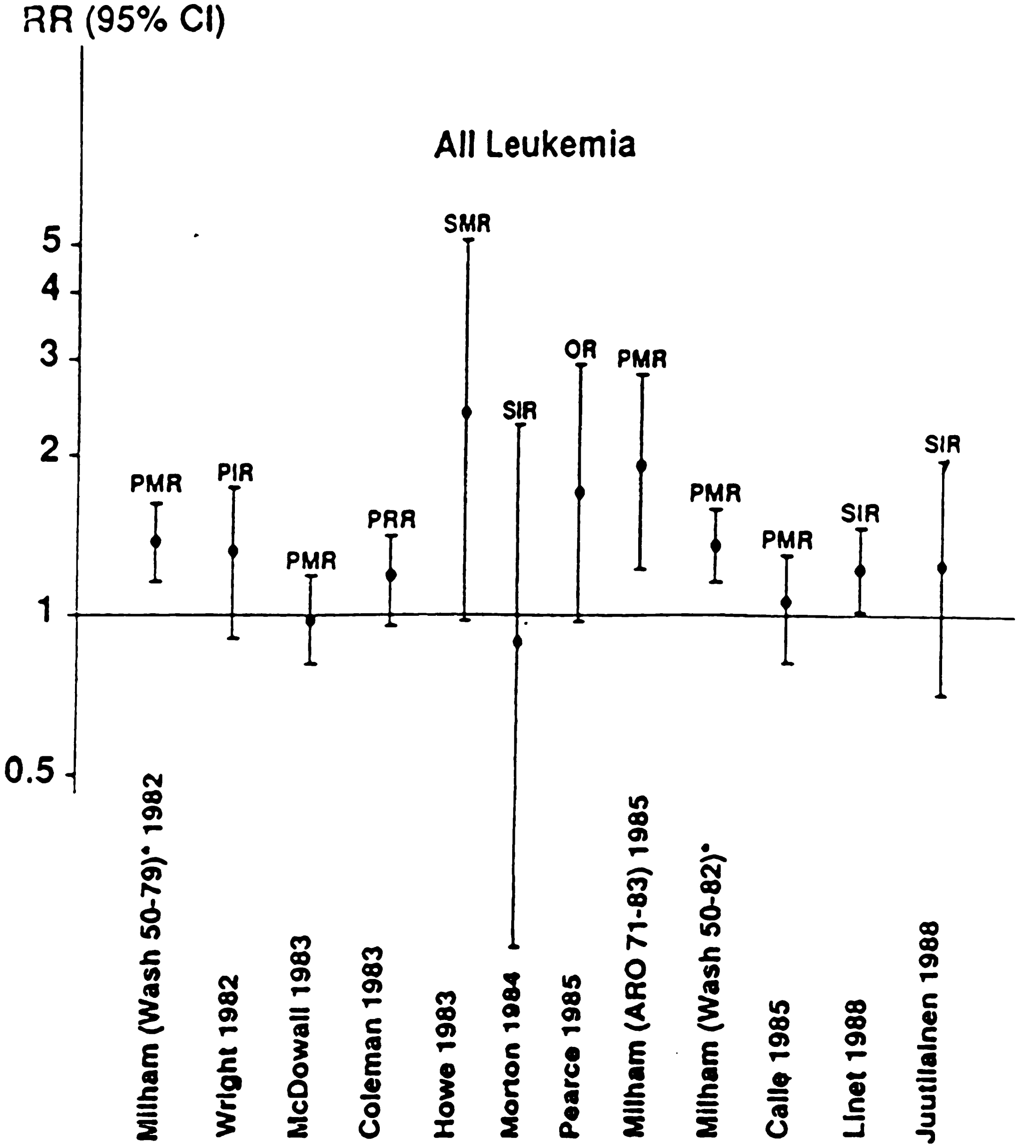
	case / control	exposure assessment		OR
Speers 1988	East Texas residents 202 glioma deaths 238 random non-brain tumor deaths	occupational history on death certificates	utility employees	13.10 (1.3- 128.9)
			electrical occupations	2.11 (0.8- 5.8)
			dose - response relationship	
Pearce 1989	New Zealand cancer Registry 80-84 452 male brain cancers all other cancers	occupation on registry forms	All electrical workers	1.01 (0.56 - 1.82)
			electrical engineers	4.74 (1.65 - 13.63)
			electricians	1.91 (0.84 - 4.33)
Savitz 1989	1095 brain cancer deaths in the US states		electrical workers	1.5 (1.01 - 2.1)
			electrical and electronics technicians	3.1
			electric power repairmen	2.4
Brownson 1990	Missouri cancer registry 84 - 88 312 white male brain cancers 1248 other cancers	occupation from hospital record (usual or longest)	communication workers	1.4 (0.5 - 4.1)
			utilities and sanitary services	0.5 (0.1 - 1.7)

1.3 Cohort studies of electrical workers:

Stimulated by the results of the cancer and leukemia studies, cohort studies of electrical workers have been conducted. Occupational groups were: telephone operators, telecommunication industry workers, linemen, station operators, telephone company workers, electrical utility workers, etc. Aiming for better results, sample sizes were large and observation periods extended over many years. Relevant results are presented in Figure 4 (4). We can observe that before 1990, although many risk ratios for leukemia and brain cancer were over one, there was no significant excess over the years. But since 1990, as a result of more homogeneity in the sample groups used for the studies, significant excesses were recorded. Cohort studies' results, tend to strongly support the possibility of an association between these cancers and exposure to EMF, as suggested by previous studies. This association stood out in the case of skin melanoma case control, rather than for brain cancer or leukemia case control studies, as was anticipated. (Skin melanoma is in excess in 5/7 cohorts).

1.4 Skin melanoma case control:

Two contradicting studies on eye melanoma among electrical workers have been conducted. [Table 3] (4). The first published by Swerdlow, reported elevated odd ratios of eye melanoma for electric and electronic workers. The second was done in four Canadian provinces by Gallagher who did not find any excesses among his cases. Although it is commonly argued that excess of skin and eye melanoma in these group of workers is more related to a higher socio-



LEUKEMIA RISKS AMONG ELECTRIC WORKERS

Figure 4. The vertical axis shows the ratio of the number of cancer cases among groups exposed to stronger fields to the number of cases among groups exposed to weaker fields. The vertical lines indicate the statistical uncertainty that results from the relatively small number of people in each case. (ref 4)

Table 3. Results of two case control studies on eye melanoma. (ref 6)

	case / control	exposure assessment		OR
Swardlow 1983	England and Wales cancer registry 2159 m. incident cases 2125 f. incident case other registrants	Occupation in registry	for electrical and electronics workers	
			1968-78	126 (8)
			1971	167 (1)
			1972	714*(5)
			1973	263 (5)
			1974	444*(4)
			1975	571*(4)
Gallagher 1985	cancer registry of 4 provinces in west Canada (79 - 81) age 20-79 65 ocular melanoma 65 random controls	occupation secured through interviews	no elevated risk found for electrical or electronics workers	

* $p < 0.05$

economic status of these people rather than the consequence of exposure to EMF, this issue should not be overlooked and deserves further attention.

1.5 Welders and EMF:

Because of the nature of their work, welders are exposed to intense magnetic fields. Welders are the workers the most exposed to magnetic fields. In 1987, Stern (4) carried an intensive review of 15 cancer studies in welders. The results are summarized in Table 4 (4). In most of these studies, lung cancer cases were high while leukemia cases were negligible. However, later studies of chronic myeloid leukemia conducted by Preston (4), reported highly elevated odd ratios in welders(OR=25.4), which is remarkable when compared to the negative results found earlier.

1.6 Male breast cancer:

Since male breast cancer is an extremely rare disease, any number of such cases would be of high concern. Recently, Matanowsky (9) conducted a study of telephone workers. The results, although reporting small numbers, indicate a high risk of male breast cancer among telephone central office technicians. Two cases were found among 9,561 workers, while ordinarily none would be expected. Urged by Matanowski's findings, Demers (10) carried out a case control study of 227 male breast cancers drawn from 10 registries from the Surveillance, Epidemiology and End Results (11) from the National Cancer Institute. He chose 300 controls through random digit dialing or from medicare eligibility lists. His results confirmed the

previously reported ratios for any exposed job(OR=1.8, CI=1.0-3.2). However, the highest odd ratios were among electricians, telephone linemen, and electric power workers (OR=6.0, CI=1.7-21.5), and radio or communication workers (OR=2.9, CI=0.8-10.2). These results are significant to cancer researchers in suggesting a proposed mechanism by which exposure to EMF interact with the melatonin hormonal system.

Conclusion:

No positive answer has yet been widely accepted concerning the magnetic fields-cancer correlation. The epidemiologic studies conducted for this issue have found some statistical evidence of such correlation, but because of the small sample sizes and the lack of EMF exposure data or assessment, no conclusions could be drawn.

II- REPRODUCTION:

Does exposure to EMF has any effect on certain reproductive concerns such as infertility, outcome of pregnancy, childhood cancer and prenatal exposure to electrical appliances?. Studies in that area can be grouped under the following subtitles:

-Outcome of pregnancy in wives of exposed workers.

-Outcome of pregnancy and use of electric blankets.

-Infertility of exposed male workers.

-Central nervous system of exposed fathers,

-Childhood cancer and prenatal exposure to electric appliances.

***Table 4**. Studies of leukemia incidence in welding populations. (ref 6)*

	all leukemia O	all leukemia RR	acute leukemia O	acute leukemia RR	lung cancer O	lung cancer RR
1)	6	0.96	4 (m)	1.71		
2)	-	--	0 (1)	--		
3)	20	0.83	13 (a)	1.04		
4)	7	2.25				
5)			--(m)	(3.8)		
6)	19	0.89	6 (a)	0.67		
7)	0	--			6	0.95
8)	0	--			17	1.5
9)	4	4.2			10	2.2
10)	4	0.35			50	1.32
11)	1	2.5			7	1.38
12)			6 (a)	1.81	27	0.99
13)	43	0.99			193	1.42
14)	15	1.14			12	1.60
15)	27	0.85	7 (m)	0.76	381	1.46
			4 (1)	0.63	305	1.27
Pooled data RR	146	0.92	40	0.92	1008	1.34

2.1 Outcome of pregnancy and use of electric blankets:

Electric blankets and heated water beds cause probably the largest and longest domestic exposure to EMF that one can get... on the order of 50 to 100 mG peak *. Manufacturers have begun marketing blankets with greater reduced magnetic field strength. Since these are in every day use, they might have an effect on pregnancy outcomes, by either acting directly on the foetus or on the gametes through some genotoxicity (4). So far, only two studies have been carried in the subject by the same authors, Wertheimer and Leeper (4) who found some correlation with house wiring configuration.

2.2 Outcomes of pregnancy of wives of exposed workers:

The only study conducted in this area was done in 1983 by Nordstorm (12), who tried to assess the effect of fathers exposure to EMF at work, and the outcomes of their wives' pregnancy. A questionnaire was addressed to active and former employees of a Swedish electrical plant. As is commonly done, exposure was assessed based on occupational history. Abnormal pregnancies were more numerous, resulting from an increase in congenital malformations among couples whose men work in high voltage switch yards.

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* Measurements made by the author's advisor indicate an exposure range of 0.05 to 95 mG ion an older electric blanket.

2.3 Infertility of exposed male workers:

In Sweden, Nordstorm (12) attempted to investigate the difficulty in attaining pregnancy in couples whose male was exposed to EMF during fertility. The report indicated difficulty rates of 20% among 400kV switchyard workers, 19% among 380-220kV transmission line workers, and only 6% among 130kV exposed workers. Thus, couples whose men work in high voltage switchyards (400kV), experience more difficulty in attaining pregnancy. Since the danger detected was related to high voltages, this is likely to be an electric field effect if there are no confounders.

2.4 Brain cancers and paternal occupational exposure before birth:

Searching for a possible relationship between childhood brain cancer and paternal exposure at birth, at least four population-based case control studies have been published. The sample sizes for these studies were large (from 157 to 499) (4), and the children's ages range was from 0 - 14 years old. Odd ratios of these studies are high, several of them reaching statistical significance. Correlating these results with the previous one which found an excess of brain cancers among workers exposed to EMF, strengthens the importance of the issue and inquires further investigations.

2.5 Childhood cancer and use of electric appliances:

Savitz (7) inquired mothers on their use of electrical appliances before and after a child's birth. His studies were published in 1990, reporting little association between the occurrence of childhood cancer and the use of electric blankets (OR=1.3,CI=0.7-2.2). An increase in leukemia and brain cancer cases was more pronounced (OR=1.7, CI=0.8-3.6) for leukemia and (OR=2.5, CI=1.1-5.5) for brain cancer.

CONCLUSION:

Some authors proposed an association between EMF exposure from electric blankets or through exposed spouses and some pregnancy outcomes, such as prolonged gestation period, low birth weight, congenital malformation, spontaneous abortion...etc. The difficulty in attaining pregnancy among couples whose men are switchyard workers may be worth pursuing, in the context of the observation made by Nordstorm (12).

III- NEUROPSYCHOLOGICAL EFFECTS:

One study (4) reported that no differences in psychiatric diseases or psychological abnormalities, were observed between exposed and nonexposed people. Results were not only negative, but Knave(4) reported that performance on psychological tests were better among exposed than non exposed workers. This has been attributed to a higher economic and educational levels for people working in high voltage substations. EMF effects have even been studied for the occurrence of suicides and depression cases.The relative results were negative.

CONCLUSION

Of the three studied effects of EMF exposure, cancer, reproduction and neuropsychological effects, cancer is the one that had raised most public and epidemiological interest.

Leukemia, brain cancer and male breast cancer are three sites where excess risks have been reported, among workers engaged in " electrical occupations". Although almost all "electrical occupations" have shown an excess of one cancer or another, the results reported are inconsistent and sometimes contradictory and confounders have not been isolated. These studies suffer from the lack of a common baseline for EMF measurements, and thus their conclusions are questionable.

Studies on the EMF-reproduction effects, have affirmed the effects of occupation on outcomes of pregnancy, male infertility and childhood cancer. In the case of magnetic fields, no measurements were taken nor were chemical or socioeconomic confounders eliminated. Psychological effects studies were negative. Some further study is needed to identify confounders.

Using conventional scientific methods, the argument that these fields cause cancer, reproductive damage, or other heath effects falls far short of being convincing. The results of the epidemiologic studies were inconsistent and often contradictory. They do suggest the existence of complex biological phenomenon.

CHAPTER THREE

EXPOSURE ASSESSMENT

I- INTRODUCTION:

Exposure assessment is defined as the determination or estimate of the magnitude, frequency of occurrence and rate of exposure of an individual or group to an agent. Based on this science, the epidemiological studies relating exposure to magnetic fields and the occurrence of cancer were subject to a major weakness: insufficiency of data on field intensities , and absence of an exposure assessment guideline (based on health effects research. This has launched numerous measurement projects and the development of instrumentation, methodologies, guidelines, and exposure models, all directed towards exposure assessment for EMF. The intent of the guidelines is not to exclude creative approaches to field measurement problems, but to set a common baseline for measurements, and thus make comparison between studies possible. Although a systematic approach to exposure assessment was proposed by EPA (13),(EPA, 1986) certain technical factors make exposure assessment for magnetic fields at low frequency difficult and complex. They include:

1. EMF are not directly sensed by humans (as is for example, sound level), and thus questionnaire methods are subject to significant errors.

2. EMF exposure is not memorable, with the exception perhaps of home appliances and electric blankets.

3. The lack of an accepted definition of exposure and dose for EMF leads to the uncertainty of what to measure. Scientific research in the area has not verified mechanisms by which low intensity EMF interacts with the human body. Without such a mechanism, there is no guidance to what characteristic of the field should be measured: magnitude, frequency, maximum....., etc.

4. The variation of the field over time due to instantaneous current (load) variations and/or movement by the subjects makes measurements inconsistent and complicated.

5. The variation in direction: The three field components corresponding to x, y, and z perpendicular axis are different. The measurement of the three components is necessary.

6. Sensing of the magnetic field via Faraday's law and a search coil implies that a motion voltage is added to the magnetic field-induced voltage, if the coil moves. This effect must be controlled or field strengths will be overestimated by orders of magnitude.

EXPOSURE METRIC

Magnetic fields are commonly expressed in tesla (T) or microtesla (μT). whereas a unit that has been used historically is the Gauss (G) or the milligauss (mG), where

$$1\ G = 10^{-4}\ T \text{ or}$$

$$1\ mG = 0.1\ \mu T$$

Technically, the unit Tesla is used for magnetic flux density, or B-field, and not for the exciting magnetic field. The magnetic field or H- field is expressed in terms of Amperes/meter (A/m). The two are related by the permeability of the medium in which the fields are established. $\vec{B} = \mu\vec{H}$. In media containing no iron, cobalt, or nickel (or related alloys), B and H are linearly related. This includes all biological and most organic media. However, for the purpose of all the field effect studies and the following chapters, the term 'magnetic field' refers to the magnetic flux density, which is a vector quantity related to the direction and magnitude of the current flow, and is expressed in units of Gauss or milligauss.

In order to set a metric for exposure, scientists should determine which feature of the magnetic field is directly related to health effects. Thus because of the absence of such information, the choice of a specific exposure metric remains arbitrary and unclear. Although several metrics are possible, the most commonly used has been the time integrated field exposure expressed in terms of mG-hr, or an average field in milligauss. In this thesis, exposure is evaluated as an average field expresses in units of milligauss.

II- SOURCES OF EMF EXPOSURE AND THEIR CHARACTERIZATION:

Unlike other environmental agents, everyone is exposed to low frequency magnetic fields (EMF) to some degree. Sources of electromagnetic field exposure range from home appliances, electric blankets, electric shavers, household wiring to distribution lines and 765 kV transmission lines. The relative contribution of different sources to overall individual exposure is not well documented and the maximum total likely varies 1 to 100 mG among individuals in urban areas. Figure 5 shows the approximate 60 Hz magnetic field strengths from various common sources (8). Note that some household and workplace appliances provide at least as much exposure as power lines. Some 60-Hz magnetic field measurements have been reported and characterized as below:

In Rural Area:

Magnetic field measured in 14 commercial and retail locations in rural Wisconsin and Michigan had a mean value of 1.1 mG (14) (ITT Research, 1984).

In An Office

Stuchly (15) reported a magnetic field exposure of 0.5 mG in an office in Canada.

Color TV:

The same study by Stuchly reported a measured field of 12.5 m G at 0.3 m away from the screen.

VDT: He also measured magnetic field levels of 1.5 to 7 mG, 0.3 m in front of video display terminals.

Welding and steel production: Welding machines and induction furnaces are potential sources of high occupational magnetic field exposure. Workers in steel production using arc or induction furnaces are exposed to 50 Hz fields as high as 1-to-100 G near the work areas (15).

Electric Transmission Facilities:

Four Canadian generating stations exhibited localized magnetic fields as high as 2.7 Gauss while the typical levels are 10 times lower. Generating plant workers in the Federal Republic of Germany may be exposed to 1-to120 Gauss fields, as reported by Stuchly (15). He also reported estimated magnetic fields above a superconducting cable carrying 13 KA of 1.4 G and 0.45 G for burial depths of 0.75m and 1.4m respectively. 13 kA is the maximum current ever present, on a steady basis, in any power system.

Proposed High School Site In Okemos, Michigan:

Measurements at a proposed high school site, near 46 kV lines, showed that, 500 feet from the line, magnetic field strengths would be typically 0.08 mG. This number is much smaller than strengths used in any health effect studies. Directly under the 46 kV line, 11.4 mG fields were reported. The typical line current was predicted to be 200 amps, while the typical daily maximum current is 310 amps. These measurements are taken from Dr. Gerald Park and Khadija's field notes, at Michigan State University.

More extensive field measurements have been reported by Bracken (14) in 1988. He investigated the fields in some electric

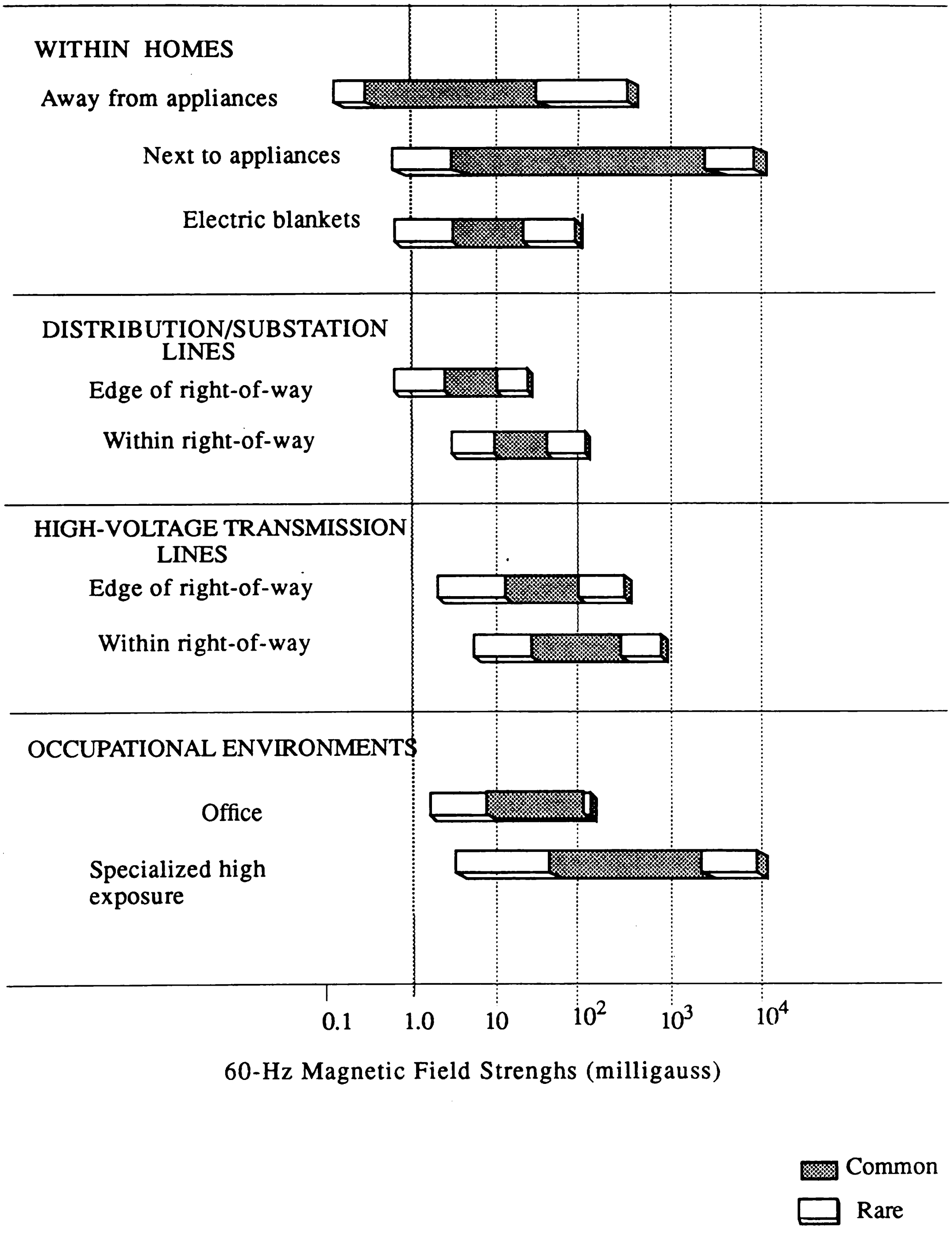


Figure 5. *Approximate strength of the average magnetic field produced within the body by several common sources.(ref 8)*

worker environments. The highest magnetic field for an electrician was near an industrial power supply, 103 mG. The second highest was near underground and overhead transmission lines for power workers, 41 mG. Sources of magnetic fields in the office environments include electrical distribution transformers and wiring in vaults that are located inside large office buildings. More than 100 mG measured directly above the transformer can be caused by large heating, cooling and lighting loads. However, most office space is under a 0.1 mG magnetic field, 5000 times less than the earth's steady magnetic field.

III- INSTRUMENTATION:

There are two complementary approaches to obtaining exposure assessment: field strength measurements and computer simulations. Field measurements can take the form of point-in-time or long term, depending on the exposure assessment proposed. Long term measurements are obtained through stationary recording systems, while for point-in -time measurements survey meters are necessary. Field measurement instrumentation must be compact, light weight, and capable of monitoring and recording data over extended periods. Alternating magnetic fields fields are usually sensed with single and multiple coils that generate a voltage, proportional to the instantaneous magnetic field. In the case of multiple (three) orthogonal coils, the resultant magnetic field is computed from the square root of the sum of the squares of the fields from the three coils, or with a one coil device, as a true rms superposition of the orthogonal field components.

Meters that are currently used in field effect studies, characterize exposure as the time integral of induced voltage in the coil (or coils) over the time the device is worn. They use either microprocessor-based data storage of the fields three orthogonal components (14), or a simple device that integrates the induced voltage (B-Field) over the period of time the device is worn. The reading produced is a single-value-time-integrated exposure. In order to remove the effect of the motion of the observer and that of the earth's magnetic field, high pass filtering is necessary.

In the United States, exposure assessment projects commence almost daily. Of 126 EMF-related research projects going on in the U.S. and other countries, 15 of them are directed towards occupational exposure (16). In 1989, the Electric Power Research Institute (EPRI), had developed an electric and magnetic field digital exposure (EMDEX) meter (16). This meter is capable of recording EMF exposure for extended times, and storing that data in the memory of an onboard computer. The device measures magnetic fields from 0 to 25,000 milligauss, and electric fields from 0 to 500 kV/m. It has a bandwidth of 40-400 Hz. Similar in function to the EMDEX is the "ElectroMagnetic Dosimeter" developed at the Institue de Recherche d'hydro-Quebec. which measures magnetic fields up to 4000 mG, and electric fields up to 40 kV/m. During measurements, it is recommended that the operator stands still, hold the meter straight and read the maximum reading the meter shows. In the case of electric fields, the measurements are more subject to errors and uncertainties. Since the human body acts like a conductor, an attenuation or enhancement of the electric field in question is likely to occur. Electric field survey meters are usually suspended in free space by an insulated handle, keeping them away from any conducting objects including the observer (17) (IEEE, 1979).

Magnetic field measurement uncertainties come from the continuously varying current loads over time. However, the most prominent issue of exposure assessment is the uncertainty about the risk from the EMF fields, which in turn, makes the improvement of the measurement techniques and procedures impossible.

IV- MAGNETIC FIELD EXPOSURE STANDARDS:

As a response to the public concern about magnetic field exposure health effects, utility regulators are beginning to set magnetic field exposure standards within and along the edge of a transmission line right of way. The majority of the standards which do exist, address the magnitude of the electric field, some address the exposure to high frequency electromagnetic fields, and only a few addressing the magnitude of the magnetic field. The table below summarizes the existing standards in 60-Hz power lines in the United States

Table 5. *State regulations limiting field strengths (18)*

		Elec Field kV/m		Mag Field mG
STATE	VOLTAGE	IN-ROW	EDGE-ROW	EDGE-ROW
Florida	500kV	10	2	200 *
	<200kV	8	2	150
Minnesota	-	-	-	-
Montana	-	-	1	-
New Jersey	-	-	3	-
New York	-	-	1.6	-
North Dakota	-	9	-	-
Oregon	-	9	-	-

* 200 mG for single circuits
250 mG for double circuits

Although all the states listed have set electric field limits, Florida is the only state that has effectively taken action to limit the magnetic field intensity along the transmission line ROW. The 200 mG maximum field exposure set by Florida stemmed from existing technology constraints and from health data (19). New York has proposed magnetic field limits to 200 mG for all new lines, at the edge of the right of way. This standard was based upon the concept that all new constructions should not increase magnetic fields beyond what they already are. Other states are applying the regulatory concept of limiting exposures to their lowest achievable (known by the acronyn ALARA), borrowed from the field of nuclear radiation protection.

Outside the United States, magnetic field exposure standards have published by some countries. USSR is the only country that has an official regulation which limits magnetic field exposure at power line frequency of 50 Hz, while the United Kingdom and the Federal Republic of Germany have proposed standards, which are not yet mandatory (20).

In the United States, constraints have gone as far as widening the right of way. Consumer Power company regulations forbids the construction of buildings within 18 feet of the center of a 46 kV line and within 36 feet of the center of a 138 kV transmission line. It is worth pointing out that these clearances required by the National Electrical Safety Code are based upon the electrical worker's safety and not upon any field reduction concept (21).

CHAPTER FOUR

MAGNETIC FIELD CONCEPT

I- PROPERTIES:

Magnetic fields in the vicinity of overhead transmission lines are caused by the current flowing in the line conductors. This current is caused by the movement of electrons in the conductor. Magnetostatics consists of the study of magnetic fields which are constant in time. Related to the magnetic field $\vec{H}$, is the magnetic flux density $\vec{B}$. They are related via the permeability $\mu = \mu_o \mu_r$ by:

$$\vec{B} = \mu \times \vec{H} \tag{4.1}$$

Where

μ = The permeability which is a property of the material in which the field is located.

μ_o = The permeability of free space (Vacuum) and is a universal constant given by $\mu_o = 4\Pi x 10^{-4}$ Henry/m

μ_r = Relative permeability with respect to that of free space.

Physical materials have a relative permeability close to unity, except for ferromagnetic materials like iron, nickel, cobalt and some ferromagnetic ceramics which have relative permeability sufficiently different from one, to be of concern. In this thesis, the magnetic field will be calculated in free space, and thus μ_r is equal to one, meaning that the permeability μ equals that of free space μ_0.

1.1 Ampere's Law :

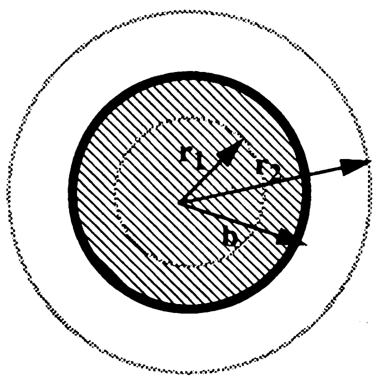
The magnetic fields around transmission lines are described by a fundamental law of magnetostatics: ***Ampere's Law*** which is expressed as:

$$\oint \vec{H} \bullet d\vec{l} = I \qquad (4.2)$$

It states that the circulation of the magnetic field around any closed path is equal to the free current flowing through the surface bounded by the path. ***Ampere's Law*** is useful for magnetic field calculations for simple geometries. This can be illustrated by the following practical case of a long straight wire carrying a constant current, which is of interest in this thesis.

Example (22): Magnetic field of a long straight wire of radius b and carrying a current I:

Consider two circles in a plane perpendicular to the conductor, of radii $r_1 \leq b$ and $r_2 \geq b$, and whose centers coincide with that of the conductor's circular cross section as shown below.



(a) Inside the conductor: $\mathbf{r_1 \leq b}$

The current enclosed by the circle of radius r_1 is

$$I_1 = \frac{\Pi r_1^2}{\Pi b^2} = \left(\frac{r_1}{b}\right)^2 \times I$$

Therefore from *Ampere's Law:*

$$\vec{B} = \frac{\mu_o \times r_1 \times I}{2\Pi \times b^2} \times \hat{\phi}$$

Where $\hat{\phi}$ is the polar coordinate unit vector along the wire.

(b) Outside the conductor: $\mathbf{r_2 \geq b}$

The area enclosed by the circle of radius r_2 contains the total current I. Thus from *Ampere's Law,*

$$\vec{B} = \frac{\mu_o \times I}{2\Pi \times r_2} \times \hat{\phi} \qquad (4.3)$$

Note that the field intensity in inversly proportional to the distance from the conductor and that $\vec{B}$ is directed tangentially to circles centered on the conductor and on planes perpendicular to the conductor as shown in Figure 6.

1.2 Conservation of magnetic flux:

The magnetic flux through a given area is determined by:

$$\phi = \int \vec{B} \bullet d\vec{A} \qquad (4.4)$$

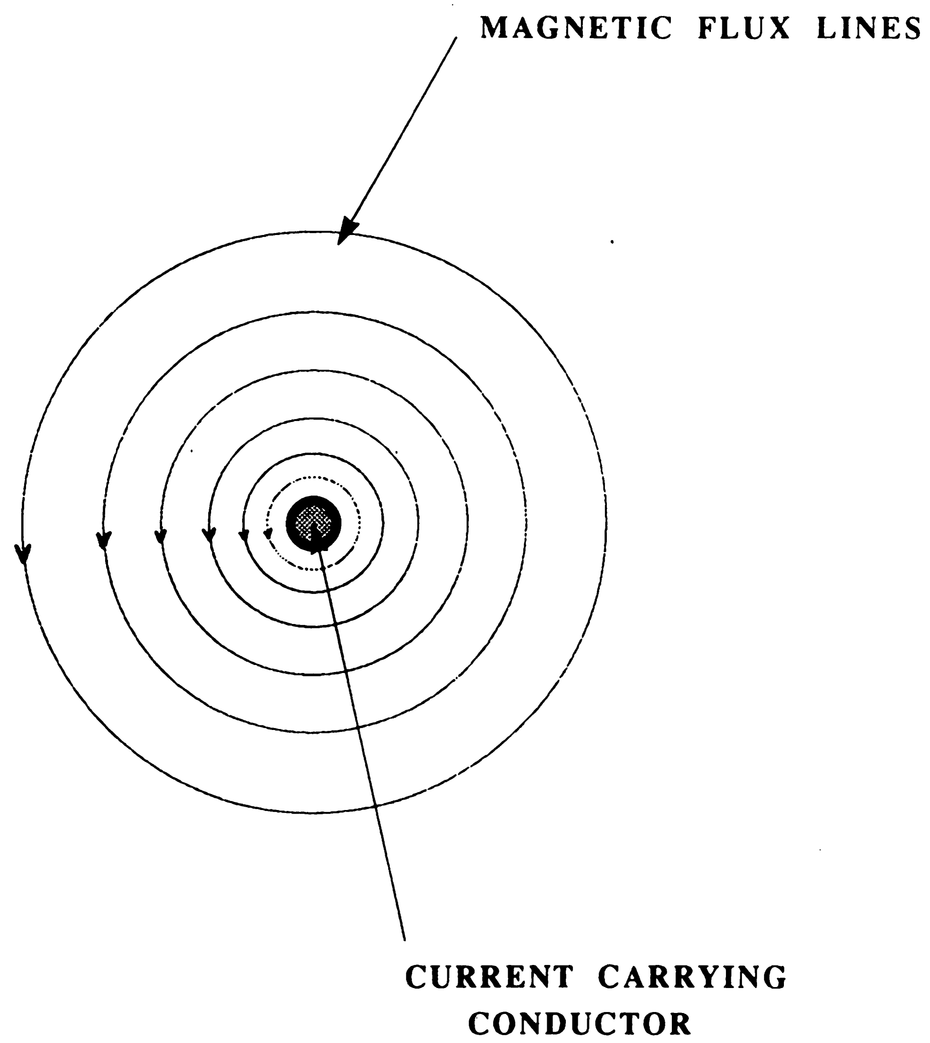
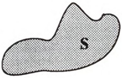


Figure 6. *Magnetic field surrouding a current-carrying conductor. When the current flow is out of the paper, then the magnetic flux lines are directed as shown.*

Over an arbitrary closed surface S, the magnetic flux vanishes as:



A closed surface S

$$\phi = \oint_S \vec{B} \bullet d\vec{A} = 0 \qquad (4.5)$$

Where the surface integral is carried out over the bounding surface of an arbitrary volume. This gives the well known result that there are no magnetic flow sources, and that magnetic flux lines are continous and always close upon themselves. Equation(4.5) is also referred to as an expression for the law of Conservation of magnetic flux, stating that the total outward magnetic flux through any closed surface is zero (22).

1.3 Magnetic forces on current-carrying conductors:

A Charge q moving with a velocity $\vec{u}$ in a magnetic field with a flux density $\vec{B}$, experiences a magnetic force $\vec{F}_m$, given by:

$$\vec{F}_m = q\,\vec{u} \times \vec{B}$$

From the expression of magnetic force, the magnetic force per unit length on a conductor of length l, is given by:

$$\vec{F}/l = \vec{I} \times \vec{B}$$

Where $\vec{I}$ is the current in the conductor, and $\vec{B}$ is the magnetic flux density at the one conductor location due to all the other

current carrying conductors. Thus, there are forces on mechanical conductors which must be considered in the design of transmission lines.

1.4 Inductance :

Suppose we have a coil with N turns, then magnetic flux linkages are denoted by λ, such that for no leakage

$$\lambda = N \times \phi \tag{4.6}$$

Inductance relates current to the magnetic flux linkages by:

$$\lambda = L \times I \tag{4.7}$$

Through Faraday's Law which will be stated later on in this chapter,a voltage

$$v = d\lambda/dt$$

or,

$$v = L\, di/dt \tag{4.8}$$

is induced by time-varying fields. Thus, the material inductance is significant for the magnetic coupling problem (1).

II- TIME VARYING MAGNETIC FIELDS:

Power transmission lines operate at 60 Hz and other low frequencies. As far as electromagnetic phenomena in concerned, these frequencies are very small. However, these currents are not constant or direct currents, and calling the transmission line fields electrostatic and magnetostatic is actually incorrect. Electric fields in ac applications are time varying and electromagnetic fields mean fields caused by an alternating electric current. Thus, transmission line fields are time varying at 60 cycles per second, commonly represented by constant fields as the "quasi-static approximation".

2.1 *Quasi-static Approximation* :

The distances involved in transmission line environmental and health effects are usually very small compared to the 60 Hz wavelength of 5,000 km. Thus it is frequently valid to approximate the magnetic and electric fields by static formulas, especially for ground level fields (1). This is the quasi-static approximation . Above the ground planes, the magnetic field has both vertical and horizontal components which are phasors with generally different phase angles. The resulting field vectors trace out ellipses as functions of time, as will be shown in the magnetic field calculations in the next chapter. The peak field value is given by the major axis of the ellipse. This value is of concern above the ground planes, under the current carrying conductor.

2.2 *Faraday's Law* :

Time varying magnetic fields induce voltages in any conductor in the vicinity of the field. According to Faraday's law, these voltages are given by :

$$v = \frac{d\lambda}{dt} \tag{4.9}$$

Since the B-field lines are circles around the current carrying conductor, the magnetic flux lines link any conductor parallel to the line. This causes a longitudinal induced voltage in the conductor. Magnetically coupled voltage is dependent on the line current, but independent of the line voltage.

CHAPTER FIVE

CALCULATIONS OF MAGNETIC FIELDS OF OVERHEAD TRANSMISSION LINES

I- INTRODUCTION:

Magnetic field calculations are necessary for the overall design of transmission lines. Recent epidemiologic studies seem to indicate the importance of magnetic in addition to electric fields. However, in contrast to E-field measurements and calculations, there has been less work accumulated for calculating, measuring and predicting the B-fields under the transmission lines. In the meanwhile, the increasing loading of transmission lines has increased the relative importance of magnetic field effects. This in turn has resulted in activity in the following areas: Calculation and measurement techniques for magnetic fields, and measurement of induced current on objects of different shapes, for all line voltage classes and line configurations.

This chapter presents the theoretical calculations of the magnetic fields in proximity to the line conductor, and the maximum field above the ground.The assumptions, coordinate system used for the calculation, as well as a list of useful definitions are first presented.

1.1 Definitions (2):

Vector:

A vector is described by a magnitude and an angle in space. It is indicated by an arrow over a capital letter ($\vec{B}$).

Phasor:

A phasor is a complex number. It is a quantity with a sinusoidal time variation described by a magnitude and an angle in time. Unless otherwise specified, it is used only within the context of steady state linear alternating systems. In polar coordinates, it can be written as $Ae^{j\theta}$ where A is the amplitude or the magnitude, and θ is the phase angle. In the following calculations, a phasor is indicated with a wave sign over a capital letter ($\tilde{E}$) or with sinusoidal functions of time [$e(t)$].

Magnetic Field:

A vector field of magnetic flux density ($\vec{B}$-field) is used to describe the magnetic field generated by currents in the conductors of transmission lines. It is defined by its space components along the three orthogonal axes. For steady state sinusoidal fields, each space component is a phasor that may be expressed by an rms value expressed in Tesla (SI) which is one weber per square meter (Wb/m^2), or by another commonly used unit: The Gauss (1mG=10 μT), and a phase as in

$$\vec{B}(t) = b_x(t)\vec{x} + b_y(t)\vec{y} + b_z(t)\vec{z} \tag{5.1}$$

Where $\vec{x}$, $\vec{y}$, $\vec{z}$ are the unit vectors along the x, y and z axis and $b_x(t)$, $b_y(t)$, $b_z(t)$ are phasor functions of time. The x-space component is

$$b_x(t) = B_x cos(\omega t+\phi_x) = B_{x,r} cos\omega t + B_{x,i} sin\omega t \qquad (5.2)$$

B_x, ϕ_x, $B_{x,r}$ and $B_{x,i}$ are the magnitude, phase angle, real and imaginary parts of $b_x(t)$, respectively.

It is also useful to visualize the vector $\vec{B}$, expressed in equation 5.1 as a vector moving in space. It can be shown that this vector rotates in a plane and describes an ellipse (Figure 8). The length of the semi-axis represents the length of the maximum field strength. A quarter period later, the field is in the direction of the minor axis, and the length of the semi axis represents its magnitude. The field in the direction perpendicular to the plane of the ellipse is zero.

Single Phase AC Field:

A single phase magnetic (electric) field is generated by conductors, energized by a single phase source of alternating current (voltage). All the field components are in phase. The field at any point can be described in terms of its time - varying magnitudes and invariant directions.

Three-Phase AC Fields:

Three-phase transmission lines generate a three-phase field whose space components are not in phase. The field is described by the field ellipse, i.e, by magnitude and direction of the major and minor semi-axes.

When the minor semi-axes is much smaller (less than 10%) than the major semi-axis, the field may be practically considered single phase. This occurs close to boundary surfaces such as ground, at a height of 1 *m*.

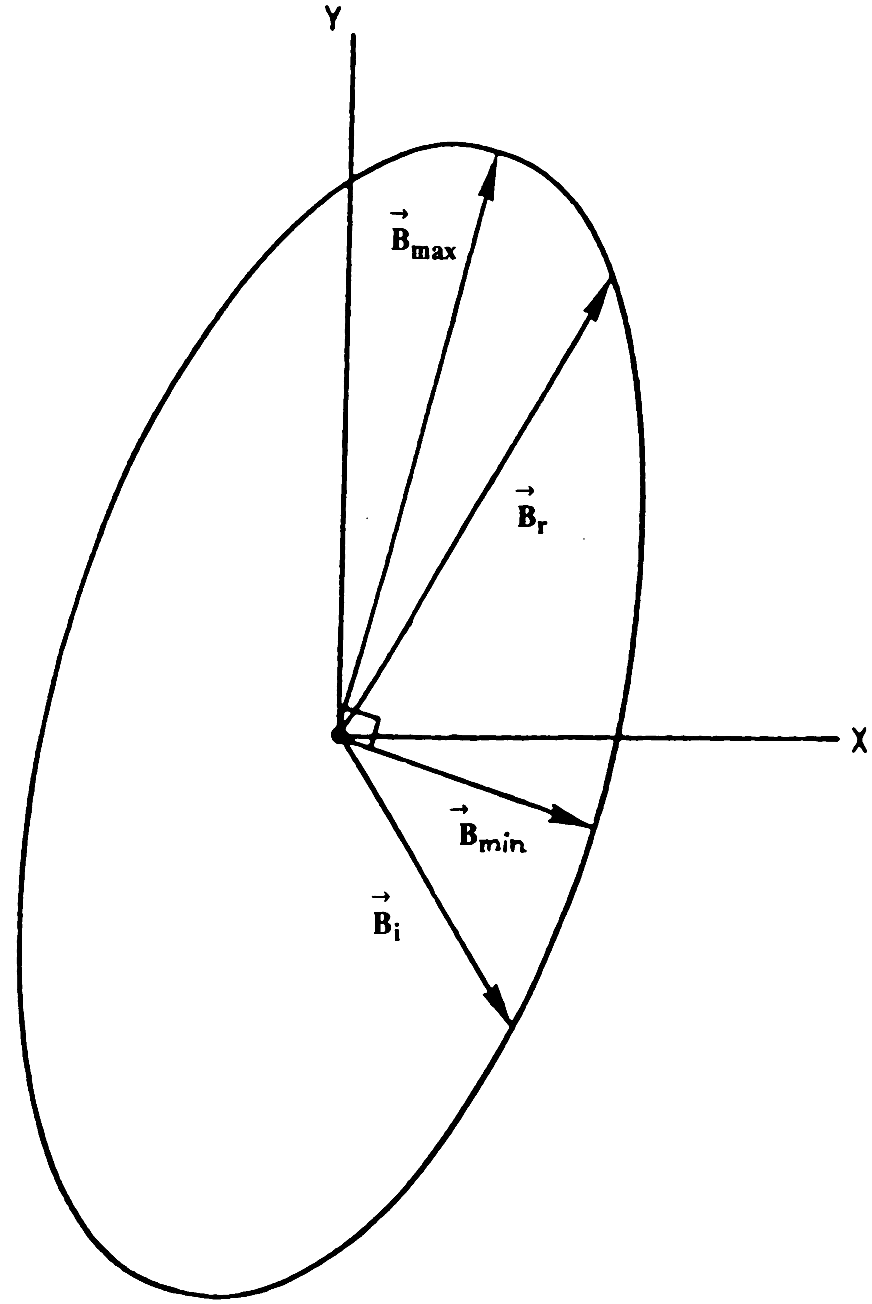


Figure 7. *Example of magnetic field ellipse at a point in time. (ref 2)*

1.2 Assumptions:

1. The calculation is sufficient using two-dimensional analysis.
2. Transmission lines are parallel.
3. The earth is a flat surface.

1.3 Coordinate system:

Consider the coordinate system with unit vectors $\hat{u}_x$, $\hat{u}_y$ and $\hat{u}_z$ along the x, y and z -axis respectively, where the Z-axis is parallel to the line. See Figure 9. (x_j,y_j) represents the observation point, while (x_i,y_i) represents the current carrying conductor point (2).

II- MAGNETIC FIELD WITH NO EARTH RETURN CURRENT:

From *Ampere's law* on page 41, the magnetic field strength, H_{ij} at point (x_j,y_j), at a distance r_{ij} from a conductor carrying a current I_i, has an amplitude

$$Hij = \frac{I_i}{2\Pi r_{ij}} \tag{5.3}$$

Where "*i*" is the index for the conductor coordinates while "j" is for the observation point coordinates, as shown in Figure 8. H_{ij} is the magnetic field intensity at the location j, at (x_j,y_j), due to the conductor i, at (x_i,y_i). In vector notation:

$$\vec{H}ij = \frac{\vec{I}i \times \vec{r}ij}{2\Pi rij} = \frac{Ii}{2\Pi rij}\vec{\Phi}_{ij}$$

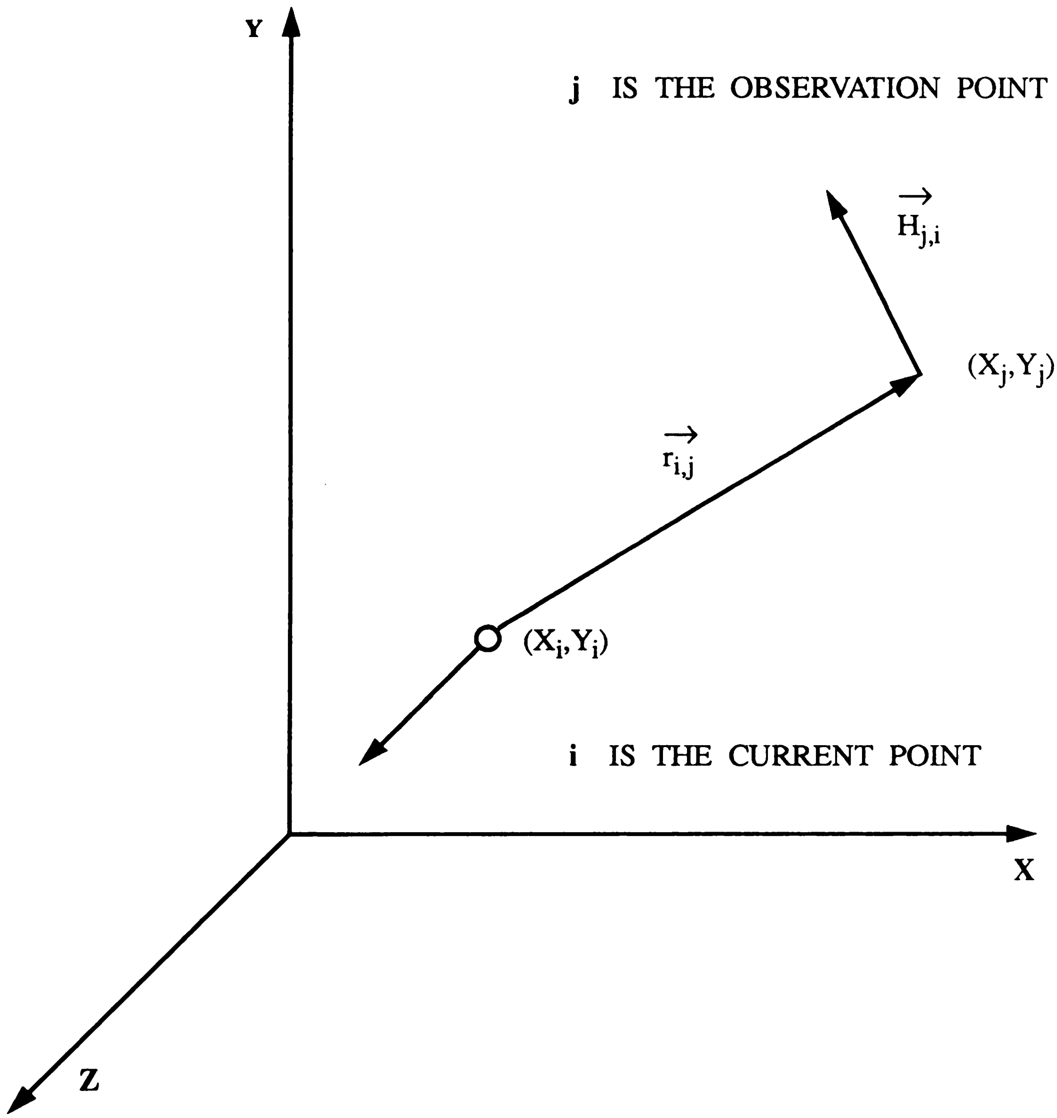


Figure 8 . *Coordinate system for magnetic field calculation.(ref 2)*

Where $\vec{\phi}_{ij}$ is the unit vector in the direction of the cross product of the vector current and the vector segment r_{ij}

$$\vec{\phi}ij = -\frac{yi-yj}{rij}\hat{u}_x + \frac{xi-xj}{rij}\hat{u}_y \tag{5.5}$$

Since there is usually more than one conductor in parallel, the total magnetic field is the sum of all the contributions from the other currents. Thus the total magnetic field at the observation point (x_j,y_j) is

$$\vec{H}j = \sum_{i}^{n}\frac{Ii}{2\Pi rij}\vec{\phi}ij \tag{5.6}$$

The magnetic flux density is

$$\vec{B} = \mu \times \vec{H} \tag{5.7}$$

Where $\mu = 4\Pi \times 10^{-7}$ H/m for both air and ground. The vertical and horizontal components of the total magnetic field are phasors which completely describe the field. Each of these components is expressed by real and imaginary parts:

$$\tilde{B}_x = \tilde{B}_{rx} + j\tilde{B}_{ix} \tag{5.8}$$

$$\tilde{B}_y = \tilde{B}_{ry} + j\tilde{B}_{iy} \tag{5.9}$$

III- MAGNETIC FIELD WITH EARTH RETURN CURRENT:

3.1 Earth Return Currents:

In most practical calculations, the magnetic fields in proximity to balanced three-phase lines may be calculated considering only the currents in the phase conductors and the lightning or neutral ground wires, while neglecting the earth return current. Calculations show that the magnetic field is primarily produced by these currents, especially at large distances from the conductor. For balanced three-phase systems, the return currents distributed in the earth, sum to zero. However such cancellation is imperfect for lower-voltage distribution lines (120V to 35kV), because the wires are often separated in space, the phase currents are often unequal, and more importantly, because some of the return currents do not follow the distribution neutral wires as they are supposed to. Instead, they may take multiple return paths through many possible ground connections from the distribution systems as well as at customer level, such as metal water pipes, to which most urban electrical systems are grounded at each house. The intensity of the magnetic fields from unbalanced currents on a distribution line tends to fall off less rapidly (1/R) than the field surrounding a set of conductors carrying balanced currents ($1/R^2$). Magnetic fields from dispersed return currents add to those from balanced distribution currents, and in some cases can form the dominant source of background indoor fields.

3.2 Calculations:

A total derivation of the magnetic field produced by each conductor and its earth return is shown in reference (2). It is expressed by the following equation:

$$\vec{H}_{ij} = \frac{I_i}{2\Pi r_{ij}}\vec{\phi}_{ij} - \frac{I_i}{2\Pi r'_{ij}}\left[1 + \frac{1}{3}\left(\frac{2}{\Upsilon r'_{ij}}\right)^4\right]\vec{\phi}'_{ij} \tag{5.10}$$

The first term is the same as equation (6.4). It gives the usual expression for magnetic fields, in proximity to the conductor (up to *100 m* for a 545 kV line(2). The second term is a correction term that accounts for the earth return current. Here the parameter Υ describes the earth conditions.

$$\gamma = [j\omega\mu(\sigma + j\omega\varepsilon)]^{\frac{1}{2}} \tag{5.11}$$

Where σ = The earth conductivity ($\sigma \approx 0.001$ to 0.002 Ohm/m)

ε = The earth permitivity ($\varepsilon \approx 8.85 \times 10^{-12}$)

$r'_{ij} = [\,(x_i - x_j)^2 + (y_i + y_j + 1/\Upsilon)^2\,]^{1/2}$,a complex number

$$\vec{\phi}'_{ij} = -\left(\frac{y_i + y_j + 2/\gamma}{r'_{ij}}\right)\hat{u}_x + \frac{x_i - x_j}{r'_{ij}}\hat{u}_y \tag{5.12}$$

Equation (5.12) is complex valued. This shows that when the earth resistivity is taken into account, the magnetic field $\vec{H}$ is not in phase with the conductor current. Note that the magnetic field vector $\vec{H}_{ij}$ can be expressed by the following real and imaginary vectors:

$$\vec{H}_r = H_{xr}\hat{u}_x + H_{ry}\hat{u}_y$$

$$\vec{H}_i = H_{xi}\hat{u}_x + H_{yi}\hat{u}_y$$

The ellipse traced by the magnetic field has axes, whose magnitude and direction are calculated in appendix A at the end of this chapter.

IV- COMPUTER SIMULATIONS:

Several PC-based computer software programs are available for calculating magnetic and electric fields from transmission lines. Some use a human activity model to study the interaction between the activity of persons and their physical environments for exposure assessment. The model is combined with engineering-based methods for calculating the electric and magnetic fields associated with the voltages and currents carried by transmission lines. Some of these PC-based programs are useful in simulating and characterizing the electric and magnetic fields for a variety of transmission line design options, and in providing some field reduction or elimination strategies. Examples include the EXPOCALC computer software package, developed by the Electrical Power Research Institute (EPRI), which provides a method for simulating exposure to transmission line electric and magnetic field during various human activities. A typical field simulation program is the TLField product of Power Technologies, Inc., which, because of the purpose of this thesis, will be described below.

TLField (Transmission Line Field)(23)

TLField is a special PC computer program developed by Power Technologies, Inc. of Schenectady, New York to evaluate and minimize electric and magnetic fields from transmission and distribution lines. This program has the capability of displaying graphic plots of the field profiles, indicating the maximum fields, in both sides of the centerline, as well as the field magnitudes at both edges of the right-of-way. TLField has the special feature of providing some techniques for line design with fields reduced to their lowest possible values. Some of its other features include:

(1) The capability of synthesizing the required voltages or currents for specially installed wires (cancellation or degaussing circuit) to minimize or possibly cancel the fields along the right of way.

(2) Analysis of cases with unbalanced currents in underground cables.

(3) The capability to reduce electric fields by erecting ground horizontal wires along the right-of-way at some critical locations.

(4) Clarity of the graphic plots: phase conductors are indicated by small diamonds, shield wires are indicated by crosses, and field cancellation/degaussing wires are indicated by small triangles. Thus a physical picture of the line configuration can be seen on the printer or screen output.

TL Field permits up to 40 conductors, including shield wires, phase conductors and ground horizontal ground wires. A maximum of 24 phases are allowed, while a maximum of only 9 shield wires and 10 ground horizontal wires are allowed. Magnetic field units are in

mG or Gauss, while a choice of a metric or English unit system is available. Fields are calculated at a height of 1*m* (metric) or 3 *feet* (British) above the ground. Their values are obtained as the resultant of the vertical and horizontal components of the field.

In this thesis, this program will be used as a tool for predicting, calculating, and exploring methods to reduce the magnetic field at the right-of-way (ROW), at 1m above the ground.

CHAPTER SIX

TRANSMISSION LINE GEOMETRY DESCRIPTION

I. Right Of Way:

Overhead transmission lines requires strips of land to be designated as Right-Of-Way (ROW)). Outside these strips, the only interference of the transmission lines with distant areas is the aesthetic effect on the landscape and radio interference. Near the energized transmission lines, within the ROW, an area of actual danger of discharge occurs, and this area can not be occupied by trees or buildings. The prohibitions are included in electrical codes and related regulations.

1.1 Definition:

The land below the danger zone defines the right of way corridor, representing an area in which the presence of the line represents constraints on the use of the land.

1.2 Size of the R-O-W:

The size of the right of way can be expressed as:

$$S_1 = 2(D + \delta + C)$$

Where

D = Interphase distance (distance between phase conductors)

δ = The maximum horizontal displacement of the midspan of the outside conductor, (and therefore related to the maximum sag).

C = A horizontal clearance which is a function of the voltage.

Table 6 give some practical values for right-of-way, inter-phase distance, midspan sag, for a three-phase circuit with various large line-to-line voltage levels.

Table 6. *Characteristics of lines for various system voltages (24).*

System voltage(kV)	420	525	765	1000	1300	1500
Midspan sag (m)	12.0	13.5	15.0	17.0	19.0	20.0
Interphase distance (m)	7.3	9.2	12.8	16.1	19.0	20.8
Right-of-way (m)	35.5	42.3	52.0	62.5	72.0	76.5

As a result of environmental awareness and increasing demand for more transmission facilities, obtaining right-of-way for transmission lines is often difficult, and for a better utilization of the land, multiple circuit designs are becoming economically attractive.

In the following chapters, we are interested in the calculations of magnetic fields in the centerline, at the edges of the right-of-way and at some distances from its edge, where planned construction might take place.

II. Height Above the Ground:

A transmission lines 'danger zone' must be kept at a given height above the ground, to allow normal activities to take place underneath them. The minimum clearance between the lowest voltage transmission lines and the ground is not less than 5.5 m. Clearance increases with voltage.

III. Conductor Spacing:

Conductor spacing is the distance between conductors as measured from the pole. These spacings are usually maintained by fiberglass-core ceramic insulators at cross-arms, which are subject to substantial field exposure. Designs must withstand conductor motion due to "wind-induced galloping" or fault currents.

IV. Conductors:

Conventional transmission lines use conductors such as ACSR*, AAAC, ACAR, SSAC and others depending on operating conditions such as compactness, maximum power transfer, wind gusts or ice exposure. However, the choice of a conductor size (cross section) is usually based on electric and economic requirements.

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* Aluminum Conductor Steel Reinforced is the most common

V. *Shield Wires:*

Overhead shield wires are installed on transmission lines to provide a path to ground for lightning protection. The use of shield wires will usually require an increased pole height, an increased pole strength, and for certain configurations an increased conductor spacing.

VI. *Bundle,Two conductor, Three conductor, Multiconductor:*

A circuit phase can consist of more than one conductor. Each conductor of the phase is referred to as a subconductor. A two conductor bundle has two subconductors per phase. These may be arranged in a vertical or a horizontal configuration. Similarly, a three conductor bundle has three subconductors per phase. They are usually arranged in a triangular configuration with the vertex of the triangle up or down. A four conductor bundle has four subconductors per phase, usually arranged in a square configuration.

For regular bundle conductors and for calculations of magnetic fields in chapter 5, away from the conductor surface, it is convenient to consider the equivalent single conductor having a diameter, d_{eq}, given by:

$$d_{eq} = \sqrt[n]{\frac{nd}{D}}$$

Where

D= The bundle diameter

n = The number of subconductors in the bundle

d = The diameter of the subconductors, which is generally the same for all subconductors.

For nonregular bundles, the equivalent diameter is calculated as the diameter of the single conductors with the same total charge. For such calculations, it is sufficient to assume a single-phase energization of the bundle.

CHAPTER SEVEN

ROLE OF LINE CONFIGURATION IN EXPOSURE TO AND CONTROL OF THE MAGNETIC FIELD

I-CONTROL OF MAGNETIC FIELDS:

In June 1990, the Environmental Protection Agency was alleged to have described magnetic fields as a "possible, but not proven cause of cancer in people' (25)*. Even though most studies show no correlation between the exposure to magnetic fields and possible health effects, public concern is already creating pressure and expectations for measures to reduce or eliminate such fields. However, in order to provide a guidance to what elimination technique should be necessary, a mechanism of how these fields interact with the human body must be in hand. Unfortunately, such a mechanism is still unknown and subject to scientific research. Exposure to magnetic fields is still an uncertain risk for possible hazards, and it has been stated by the director of the EPA that "We

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* This was in a preliminary draft of a report/ leaked to the press.

don't really understand the risk well enough to know whether one exists, and we can't give guidance to what kind of avoidance technique really would be important" (25).

Some published articles demand exposure standards and the related measurements necessary for magnetic field control. Some IEEE members have called for such standards. A working group of IEEE standards coordinating committee 28 (The Committee on Nonionizing Radiation) is considering guidelines for limiting magnetic fields. In the meanwhile, utilities are seeking and identifying methodologies for magnetic field exposure reduction. So far, possibilities for new techniques and equipment are being explored, to limit magnetic field exposure for power line maintenance workers. Transmission line designs that are in use are being reviewed from a new perspective: Field exposure reduction.

II- UNCERTAINTIES OF FIELD CONTROL TECHNIQUES:

Intensity, duration of exposure, frequency, orientation, exposure spikes, are all aspects of magnetic fields in the vicinity of current carrying wires. However, which approach should be taken for magnetic field reduction is still uncertain. Even after many laboratory and epidemiologic studies, at least four uncertainties have not been clarified.

***1) Intensity*:**

If exposure to magnetic fields is harmful, would one associate stronger fields with higher risk of diseases?. Such an intensity-effect relationship has not been demonstrated yet. The first epidemiologic studies that focused on magnetic fields, have shown average flux densities measured indoors of only 2-3 mG, whereas many common sources of exposure are known to produce field intensities of tens or hundreds of milligauss.

***2) Duration*:**

How is the effect of chronic exposure to low level fields compared to brief exposure to more stronger fields?. This has not been known yet, and thus limiting human exposure is difficult.

***3) Frequency*:**

Magnetic fields are time varying, fed by alternating currents that change direction and intensity 60 times a second, for 60-Hz power frequency (US). It has been suggested that magnetic fields are harmful only at certain frequency bands, and certain intensity ranges, or even through the harmonics created by certain loads.

***4) Orientation*:**

There is a suggestion that ac magnetic fields may interact with biological systems on the cellular level if the field frequency is in phase with the resonant frequency of certain cellular ions within the mostly static dc magnetic field of the earth itself. Biological effect occurs if the ac fields are parallel to the earth's

dc fields.

Rather than wait until these uncertainties are clarified, it may be prudent to explore field intensity minimization as a precautionary measure.

III- LINE CONFIGURATION AND REDUCTION OF MAGNETIC FIELDS:

2.1 INTRODUCTION:

The magnetic field at ground level in the vicinity of a single or multiple-phase line circuit results from the contribution from every single current-carrying conductor. Thus, the line configuration is critical for changing the magnetic field under or close to the transmission lines, in particular along the edges of the right of way, which is of concern. Numerous three-phase circuit configurations are being used by utilities for high and low voltage transmission. There are three-phase horizontal circuits, vertical, delta and vertical delta configurations, single circuits, double circuits, shielded or unshielded circuits, bundled or compact circuits with different with different phase arrangements,...etc. Some parameters are very critical in line design. They include:

- Line configuration
- Height above the ground
- Conductor sag
- Conductor mechanical parameter (metal, diameter,...)
- Line phase spacing
- Phase arrangement

- Shield wires

The arrangements of the phases in a typical three-phase transmission line is designed to cancel parts of the magnetic field, more than a few meters away. Design constraints range from natural factors such as the wind, snow, maximum temperature and ground resistivity, to economic factors such as construction and maintenance cost limitations. In chapter 5, it has been shown that the resistivity of the ground has an effect only at large distances from the phase conductors (> 100m for 550kV lines). Different mechanical and electrical line configurations generating magnetic fields have been investigated by the Electrical Power Research Institute (EPRI), at EPRI's High Voltage Transmission Research Center (HVTRC), operated by General Electric Company at Lenox, Massachusetts (25). The reader must remember that the magnetic field is produced by current, and the greater the current, the greater the field.

2.2 VOLTAGE INCREASE:

Magnetic fields vary in intensity as a function of the amount of current flowing in the conductor. Consider the simplified power transmission model shown below:

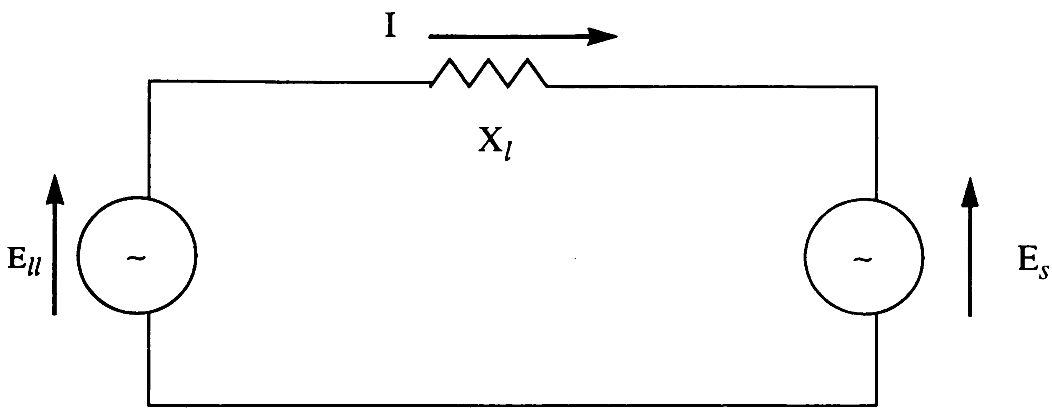


Figure 9. *Simplified power transmission model (26).*

For this circuit, the power transfer over the line is given by:

$$P = \sqrt{3} \times \frac{E_{ll}Es}{X_l} \sin(\delta) = \sqrt{3} \times E_{ll} \times I_l \times \cos\theta \qquad (8.1)$$

Where:

P = The real power transferred.

E_{ll} = The line-to-line generator voltage

I_l = The line current

Es = The remote system line to line voltage

X_l =The total inductive reactance between E_{ll} and E_s including the reactance of the transmission line and the terminal connection.

δ = The angle between the source and the remote system voltages, called the power angle.

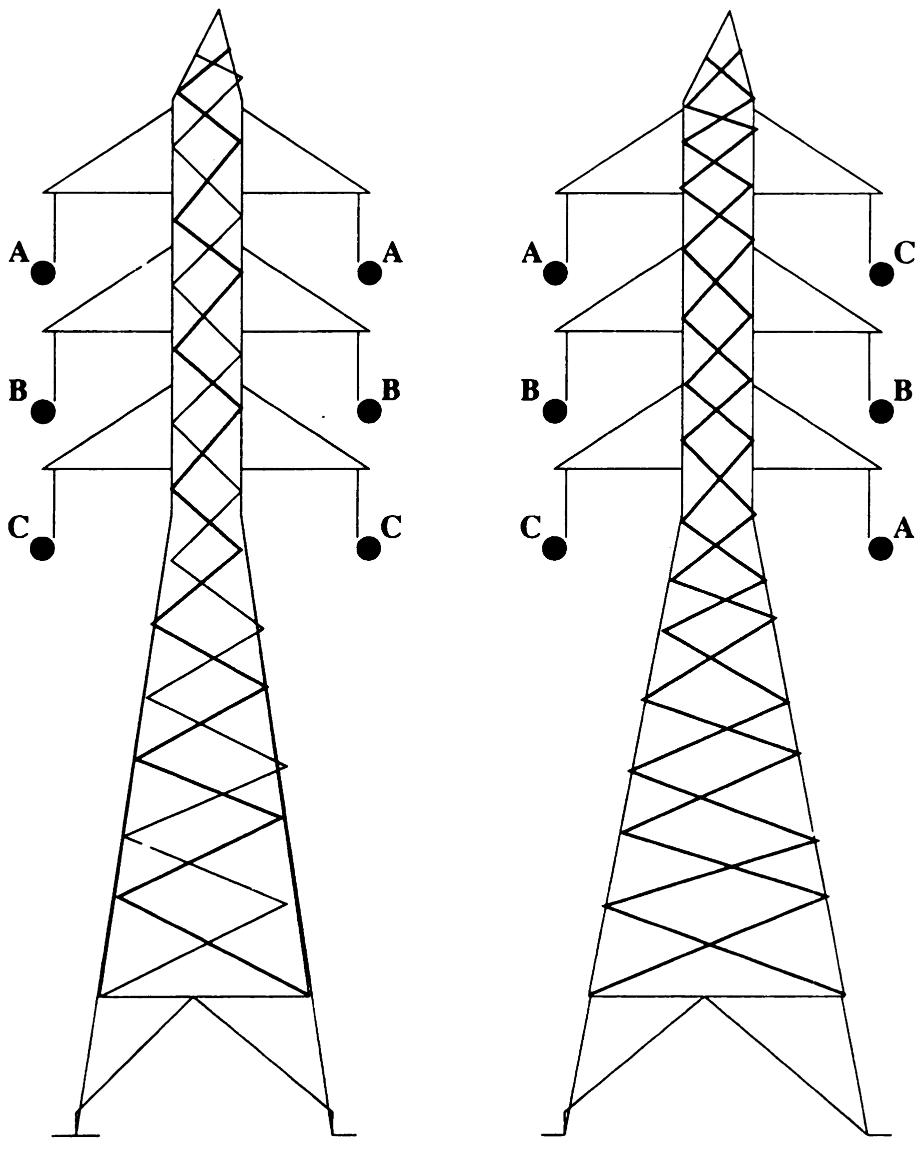
θ = The angle between the voltage and the current at the

line end.

For the same amount of power, a high voltage circuit would carry less current than a low voltage circuit, and assuming current flows were balanced, a lower magnetic field would be produced. Even though this suggestion is theoretically effective, its realization is very costly: It requires redesigning and replacing virtually every equipment involved in the transmission system. On the other hand, as current flow increases over the years, the magnetic fields might approach the intensity experienced at lower voltages.

2.3 LOW REACTANCE CIRCUITS:

Characteristic line reactance and capacitance can be used as design parameters to reduce the magnetic field in the center line and along the ROW. A typical three-phase double circuit configuration used is shown to the left in Figure 10. The field can be reduced by the reverse phase arrangement shown to the right. On one side of the tower, the conductors are vertically arranged as A, B, C from top to bottom, whereas the conductors on the other side are phased CBA. In order to maintain the balance of current flows in the six conductors, both circuits must be connected to the same busses at both ends. At the substations, changing the conductor bus connections is necessary. It is important to recognize that, since the power transmitted is inversely proportional to the inductive reactance of the system (equation 8.1), a lower reactance sets a higher maximum transmitted power by the line. Low-reactance, reverse phase configurations provide a significant



Typical three-phase double circuit configuration

Low-field, low-reactance reverse-phase configuration

Figure 10.

magnetic field reduction, when compared with similar circuits with conventional orientation. The reduction is due to the time varying magnetic fields of one circuit substantially cancelling oppositely-phased fields of the other circuit. This design technique is described by utilities as being feasible either for new lines or when upgrading existing circuits for more capacity.

2.4 COMPACT LINE CONFIGURATION:

Reducing the spacing between the conductors results in a more compact circuit. Compact line design has been of interest because compact implementation allows more circuits in an existing right-of-way (ROW). Depending on the degree of compaction, the magnetic field above the ground is reduced. Disadvantages of this design option include an increased risk for flashover and corona discharge (23), which in turn can cause an undesirable audible noise or radio frequency interference and reduce line reliability.

2.5 HIGH-PHASE ORDER TRANSMISSION DESIGN:

It is possible to use six to twelve phases, rather than the conventional three-phase configuration. Greater field reduction results. Multiple-phase circuits have also been used as a technique to maximize power transmission capability through existing or narrower ROWs.

2.6 DELTA CONFIGURATION:

The three phase conductor of single circuit transmission lines are usually arranged in a flat configuration, using H-frame or

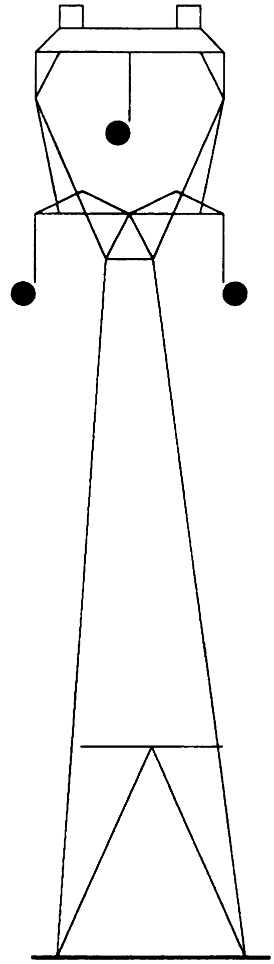


Figure 11. *Delta configuration on a lattice tower. The central conductor can be raised above the outside two in a regular delta configuration to achieve some magnetic field cancellation.*

lattice towers. Significant cancellation can be obtained if the center line is elevated above the two outside conductors, in a triangular arrangement. An inverted delta configuration is obtained by elevating the two outside conductors, above the middle one, which results in a similar field reduction. This was proposed for use in Sweden (23). Delta configurations have the additional advantage of using a narrower right-of-way and still satisfying the field reduction requirements. A typical delta configuration is shown in Figure 11.

2.7 UNDERGROUND CIRCUITS:

Magnetic fields can be minimized or even substantially cancelled by installing transmission lines underground, in certain specific configurations. Other configurations, such as for single phase distribution lines, could critically increase the field(23). Even though the earth around the underground wires provides negligible magnetic shielding, when a three-phase circuit is installed underground, a large cancellation of magnetic field occurs even a few inches away. This desirable cancellation is due to close conductor proximity and occurs only if the current flow in the transmission lines is balanced, which is seldom the case in many distribution circuits.

Underground power transmission is widely used in and around major cities for esthetic reasons. However, because of their high cost (3 to 10 times that of overhead lines), and because of their repair and maintenance difficulties, underground transmission is

usually not justified, except in urban areas.

2.8 SHIELD WIRES OR DEGAUSSING CIRCUITS:

This magnetic field reduction technique will be described and simulated in the following chapter. Furthermore, the TLField program will be used as a tool for attempting to design a degaussing circuit, for the case studies presented in Chapter Eight.

CHAPTER EIGHT

CASE STUDIES

I- USING A DEGAUSSING CIRCUIT:

1.1 Degaussing circuit specification:

Here we explore ways to force currents of various magnitudes and phase angles through conductors above the ground, to reduce the overall magnetic field, especially at the right-of-way. This can be achieved by inserting a 'Degaussing Circuit', consisting of two additional conductors of the same type as the phase conductors, installed at the edges of the right-of-way or beyond. When a current is fed via one conductor, it returns via the other one. Since these current carrying conductors are in proximity to the phase conductors, they contribute to the overall magnetic field in the right-of-way zone. Once the location of these conductors is specified, the TLField program will make a search for the currents and phase angles for this degaussing circuit which reduce the field at the ROW boundary. The specific values that show the greatest field reduction along the right -of-way are saved and then printed. The graphic plots will show the location of the two additional

conductors marked by two small diamonds, and will print out the currents and phase angles used for the plotted data.

1.2 TLField Plots:

TLField plots the normal magnetic field, then the reduced field with the degaussing circuit. On the plots, the maximum values of normal and reduced fields are displayed for both left and right halves of the field plot and at the right-of-way edges (ROW), as well as the X-coordinate where the maxima occurred, and the magnetic fields at the edges of the right-of-way. Conventional shield wires are located on the field plots by X's, phase conductors with small rectangles, and magnetic cancellation or "degaussing" wires with small diamonds.

II- INCREASING THE CLEARANCE ABOVE THE GROUND:

From chapter 4, equation 4.3, recall that the magnetic field intensity around the transmission conductor is inversely proportional to the distance from it. Therefore, in the following cases, we will evaluate and simulate the effect of using higher circuits on the reduction of the magnetic field intensity at the edges of the ROW. Higher circuits increase tower costs and may increase aesthetic sensitivity to their appearance.

CASE 1: 13.2 kV DISTRIBUTION CIRCUIT DELTA CONFIGURATION

Objective:

This line configuration was provided by the 'BOARD OF WATER AND LIGHT', a municipal utility. It is a typical configuration for a distribution feeder, encountered in residential areas. Our objective is first to predict the magnetic field at one meter above the ground, in the normal situation, i.e. for the line configuration as it exists now. Next, some modifications are evaluated, to reduce the field intensity to its lowest feasible value.

Specifications:

. Line-to-line voltage.. 13.2kV

. Full load rating (Current at maximum load).......... 350 A
(Approximately 8 MVA Maximum load)

. Typical load rating (Current at typical load).......... 250 A
(Approximately 5.7 MVA typical load)

. Height above the ground for calculation.................. 3 ft

. Number of phase conductors..................3 of 1272 Kcmil

. Conductor diameter... 1.4 in

. Height above the ground .... 37 ft

. Right-of-way width .... 34 ft

. Neutral wire .... 3/O Aluminum

. Shield wires .... None

. Ground resistivity .... 100 Ohm-m

Spacial geometry and dimensions:

Figure 12 shows the delta circuit and its dimensions.

CASE 1.1: Normal field

On Figure 13, a plot of the normal magnetic field at a typical load of 250 amperes is shown. Note that the vertical axis is located in the centerline of the right-of-way. Because of the symmetry of this delta configuration, the magnetic field is symmetric as well. The maximum field and the field at the edges of the ROW are shown.

CASE 1.2: Degaussing circuit specifications

A two-conductor circuit is inserted nearby and parallel to the phase conductors. Depending on their location, a change in the magnetic field intensity occurs. Locating the degaussing circuit along and close to the two outside conductors of the delta-circuit, results in a large field reduction. The TLField program calculations show that the field at the ROW has decreased from 6.85 mG to 0.85 mG, a reduction of 87.59%. Figure 14 shows both the field without the degaussing circuit (Normal field), and after the reduction. The reduced curve is the lower one, only 12% of its normal height (Table 7).

Table 7. *Magnetic field reduction of case study 1.2.*

Right Edge	Normal Field (mG)	Reduced Field (mG)	Decrease %
B at The ROW	6.85	0.85	87.59
B-maximum	8.51	0.88	89.66

This reduction can be achieved only by supplying the two conductors by the currents and phase angles specified by the computer output represented in Table 8.

Table 8. *Degaussing circuit specification for case study 2.1.*

Conductor No	X (ft)	Y (ft)	Current (Amps)	Phase Angle (Degrees)
4	-3.50	+35.00	187.50	+210
5	+3.50	+36.00	187.50	+30

Providing such currents involves capitol and operating costs and careful and expensive engineering evaluation. These are very important factors not addressed here.

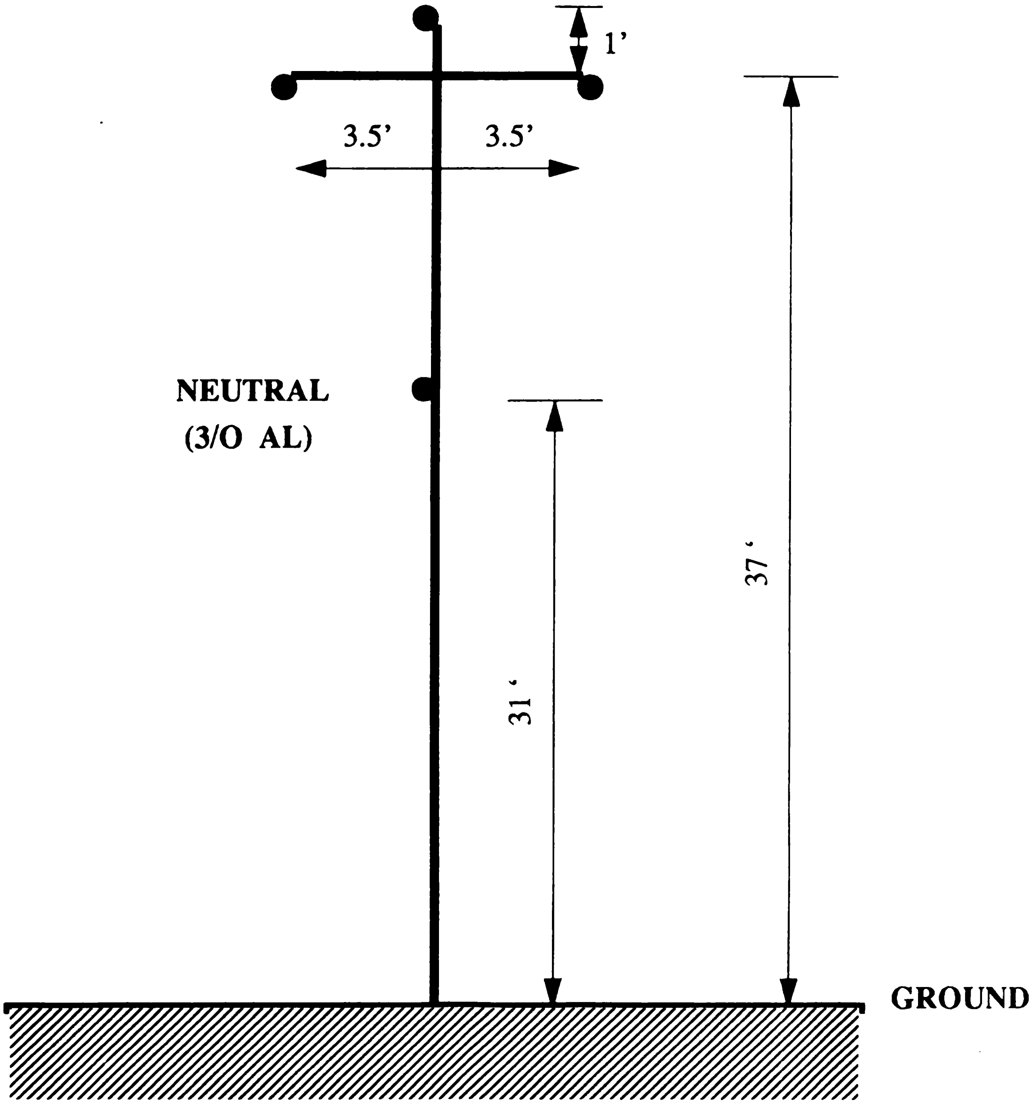


Figure 12. *13.2 kV distribution circuit, 350 amps full load rating. Typical load 250 amps. Delta configuration.*

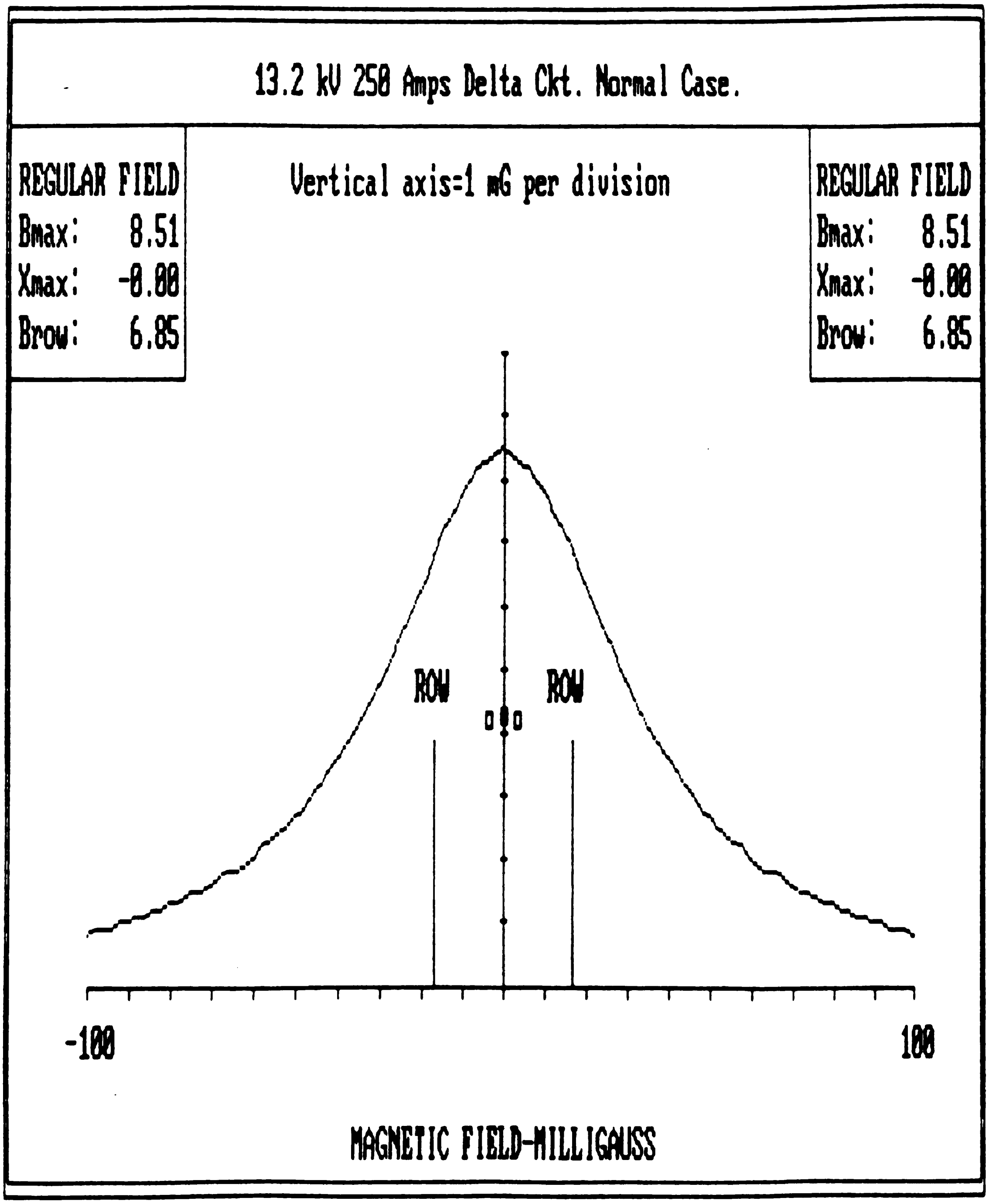


Figure 13. Magnetic fields of a 13.2 kV, 250 amps three-phase circuit, mounted in a typical delta-configuration. Normal case.

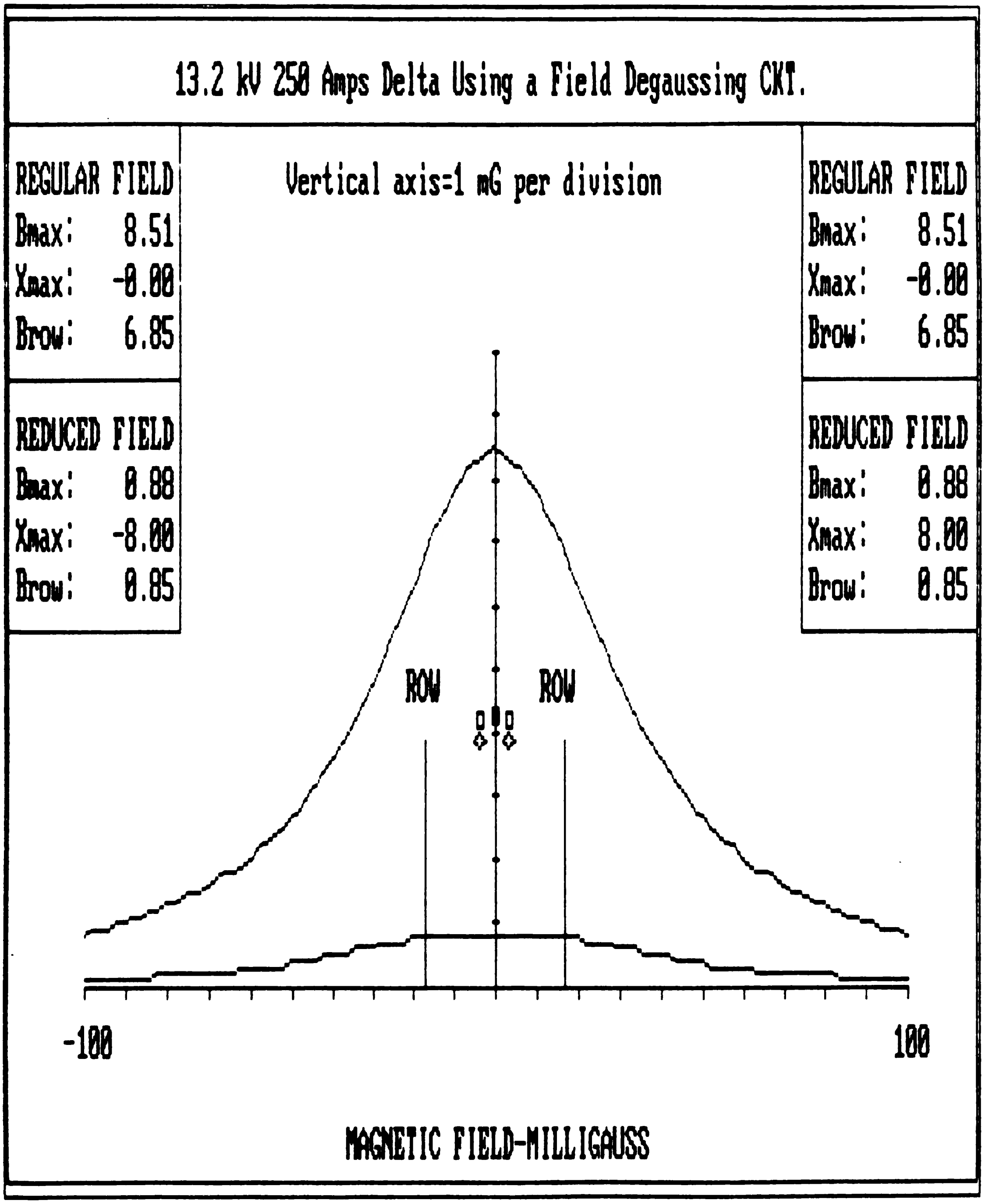


Figure 14. *Magnetic fields of a 13.2 kV, 250 amps three-phase circuit, mounted in a typical delta-configuration. The upper curve represents the normal field, while the lower curve represents the field after being reduced by the insertion of a "degaussing circuit".*

CASE 2: 138 kV SINGLE CIRCUIT TOWER VERTICAL DELTA CONFIGUTATION

Objective:

This is an other line configuration from the 'BOARD Of WATER and LIGHT', a typical configuration for medium voltage transmission. Many thousands of miles of similar lines operate in North America.

The objective is to analyze the normal case magnetic field produced by this circuit and to modify the circuit to get the minimum possible field.

Specifications:

. Line-to-line voltage .... 138 kV

. Full load summer rating (Current at full load)... . 1325 A

. Normal load rating (Current at normal load)........ 247 A

. Height above the ground for calculations ....1 m

. Number of phase conductors 3

. Number of conductors per bundle............................. 1

. Phase conductors ....1272 Kcmil

. Conductor diameter... 1.4 in

. Neutral wire ....None

. Shield wires .... 7No.8 AM

. Height above the ground (For Calculations).............3 ft

. Right-of-way .... 34 ft

. Conductor diameter.. 48 ft

. Ground resistivity.................................. 100 ohm-m

Spacial geometry and dimensions:

Figure 15 shows the line configuration and its dimensions.

Normal magnetic fields at Normal and Typical Loads:

Figure 16 shows the magnetic field curve for a typical load current of 247 ampere, at 100 m from the centerline of the right-of-way. The vertical axis is located at the centerline of the ROW. Note that because of the asymmetry of the vertical delta configuration, the magnetic field is not symmetric and higher at the side of the two vertically arranged conductors. The magnetic field at the ROW is found to be 19.80 mG at the right edge and 25.33 mG at the left edge. At 100 m from the circuit, these values decrease to 5 mG and 4 mG, respectively. Note that this range of values is comparable to what has been measured in numerous magnetic field exposure studies.

The normal magnetic field at maximum load, i.e at 1325 amps current, is shown in Figure 17, exhibiting a calculated magnetic field of 106.22 mG and 135.89 mG at the right edge and the left edge of the right-of-way respectively. At 100 m from the circuit these values reduce to 20 mG and 25 mG respectively.

Reduction of field intensity will be analyzed through two methods. First, a two-wire degaussing circuit will be installed along the two conductors that will show the most reduction. Second, the effect of an increase in the height above the ground of the overall circuit will be investigated.

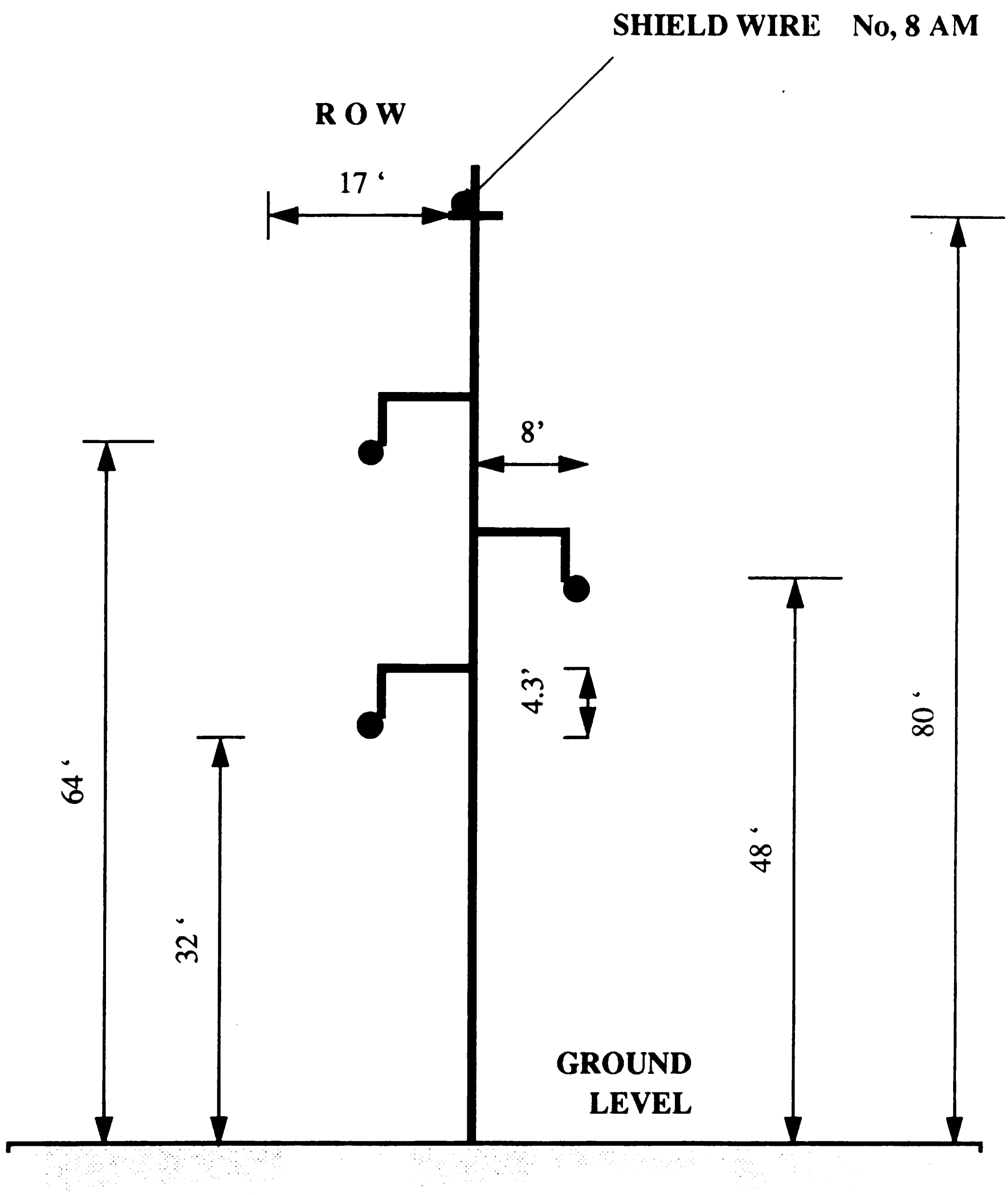


Figure 15. *138 kV single tower circuit, 1325 amps, full load rating. Typical load 247 amps. Vertical delta configuration.*

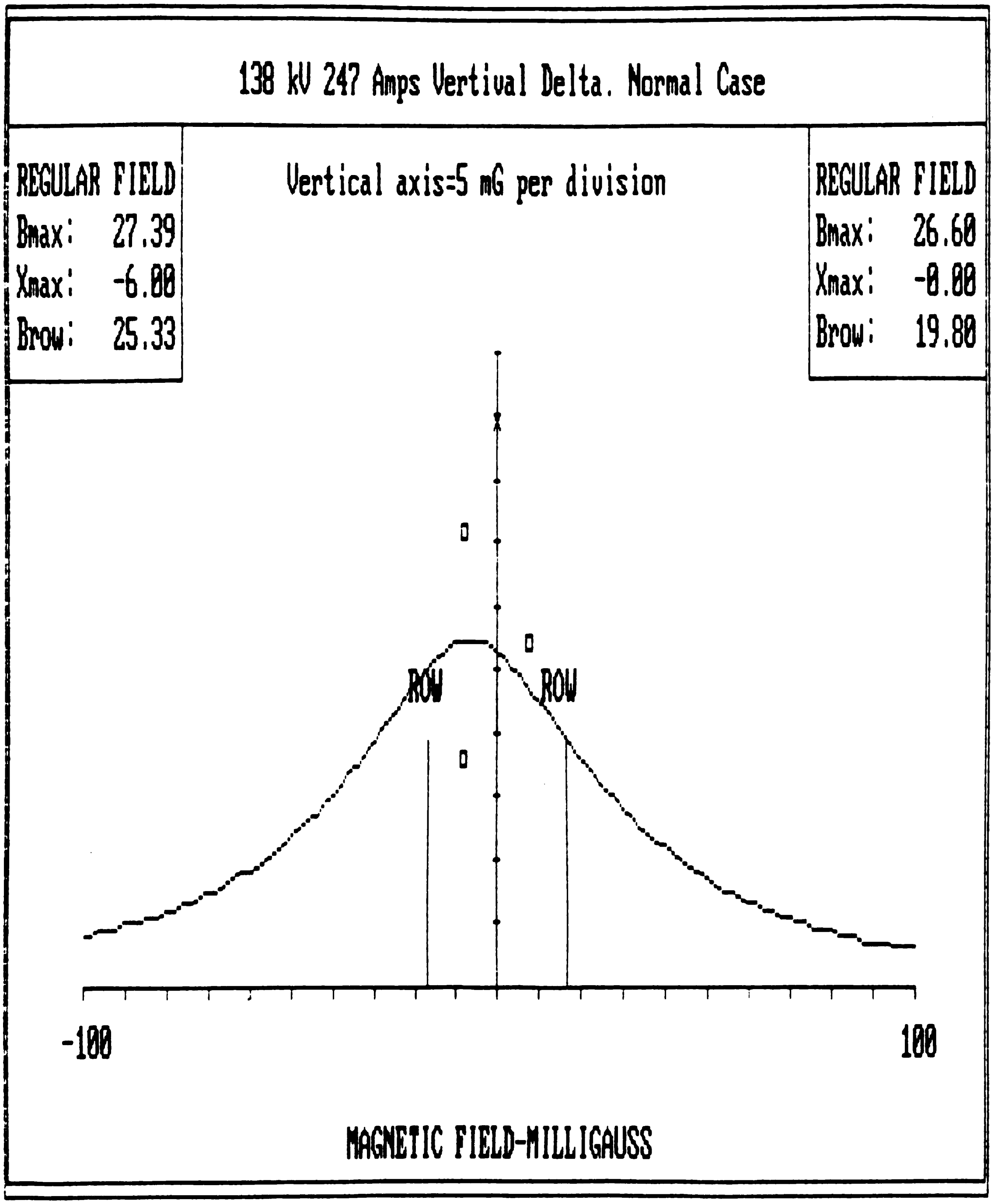


Figure 16. Magnetic field of a 138 kV, 247 amps (typical load), vertical delta circuit. Typical load, normal case.

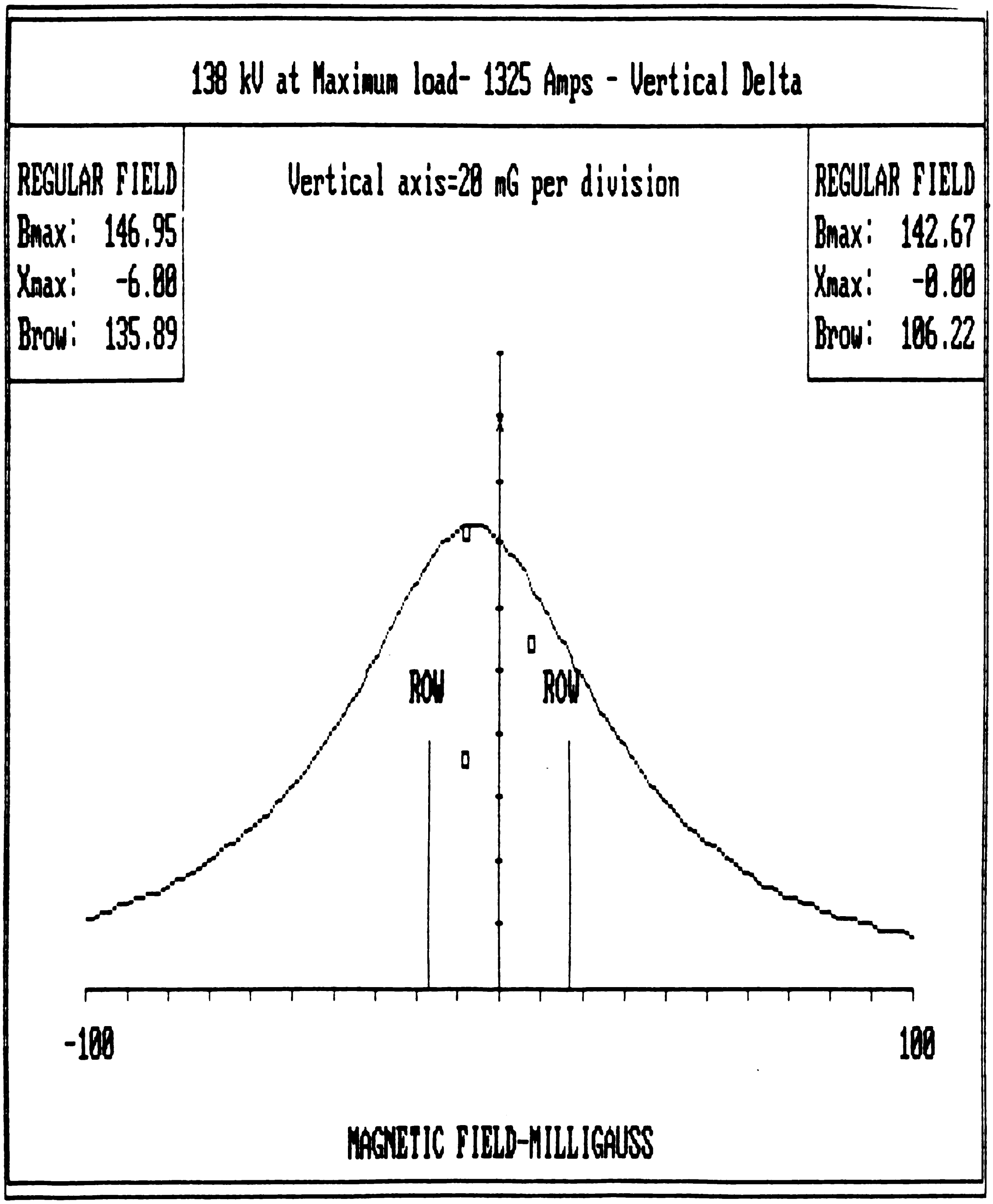


Figure 17. *Magnetic field of a 138 kV, 1325 amps (Maximum load), vertical delta circuit. Maximum load, normal case.*

CASE 2.1 Degaussing Circuit Specification:

A degaussing circuit is used for the 247 amps typical load circuit.The specifications of the degaussing circuit used.i.e the location of the two wires and the phasor currents required for the field reduction, are simulated by TLfield and summarized in Table 9.

Table 9. *Magnetic field reduction of case study 2.1.*

Conductor No	X (ft)	Y (ft)	Current (Amps)	Phase Angle (Degrees)
5	-12.00	+62.00	187.25	+210.00
6	-12.00	+30.00	187.25	-60.00

With this degaussing circuit, the TLField plot of the maximum field intensity at the ROW is shown in Figure 18. The lower curve represents the magnetic field intensity of the reduced field, while the upper curve represents the normal field. The relative calculations show that the field at the right edge of the ROW has decreased from 19.80 mG to 10.72 mG, a reduction of 45.86 %. Note that the reduced curve is only 42.56 % of its normal height.

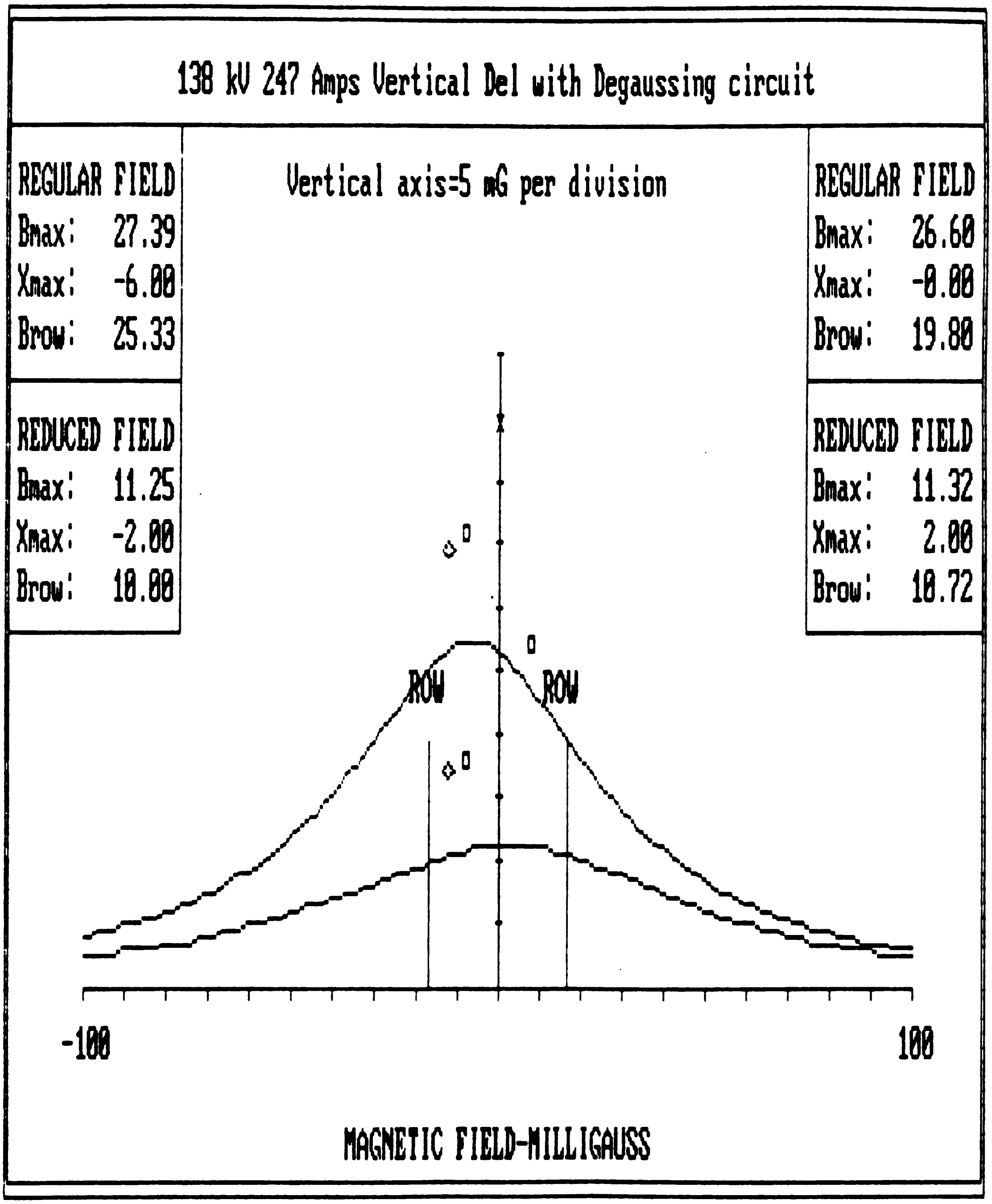


Figure 18. Magnetic field of a 138, 247 amps (normal load), with a "degaussing circuit inserted along the circuit. The upper curve represents the normal field, while the lower curve represents the reduced field.

Table 10. Degaussing circuit specification for case study 2.1.

Right Edge	Normal Field (mG)	Reduced Field (mG)	Percentage Decrease(%)
B at The ROW	19.80	10.72	45.86%
B-maximum	26.60	11.32	57.44%

CASE 2.2 Increased Height Above The Ground:

Since the magnetic field intensity around a transmission line decreases as the distance away from it increases, by implementing the transmission wires at a higher distance above the ground, the field intensity reached at the ground level would diminish. In this case, the 247 amps circuit geometry is modified by heightening the wires by 20 ft.

Figure 19 shows the reduced field, for the modified circuit which is 20 ft higher than the original one. The value for the fields at the ROW, the maximum values and the percentage reduction are summarized in table 11.

Table 11. Magnetic field reduction of case study 2.2.

Right Edge	Normal Field (mG)	Reduced Field (mG)	Percentage Decrease(%)
B at The ROW	19.80	10.18	48.59 %
B-maximum	26.60	11.69	56.05 %

Note that the reduction obtained is comparable to that obtained by using a degaussing circuit.

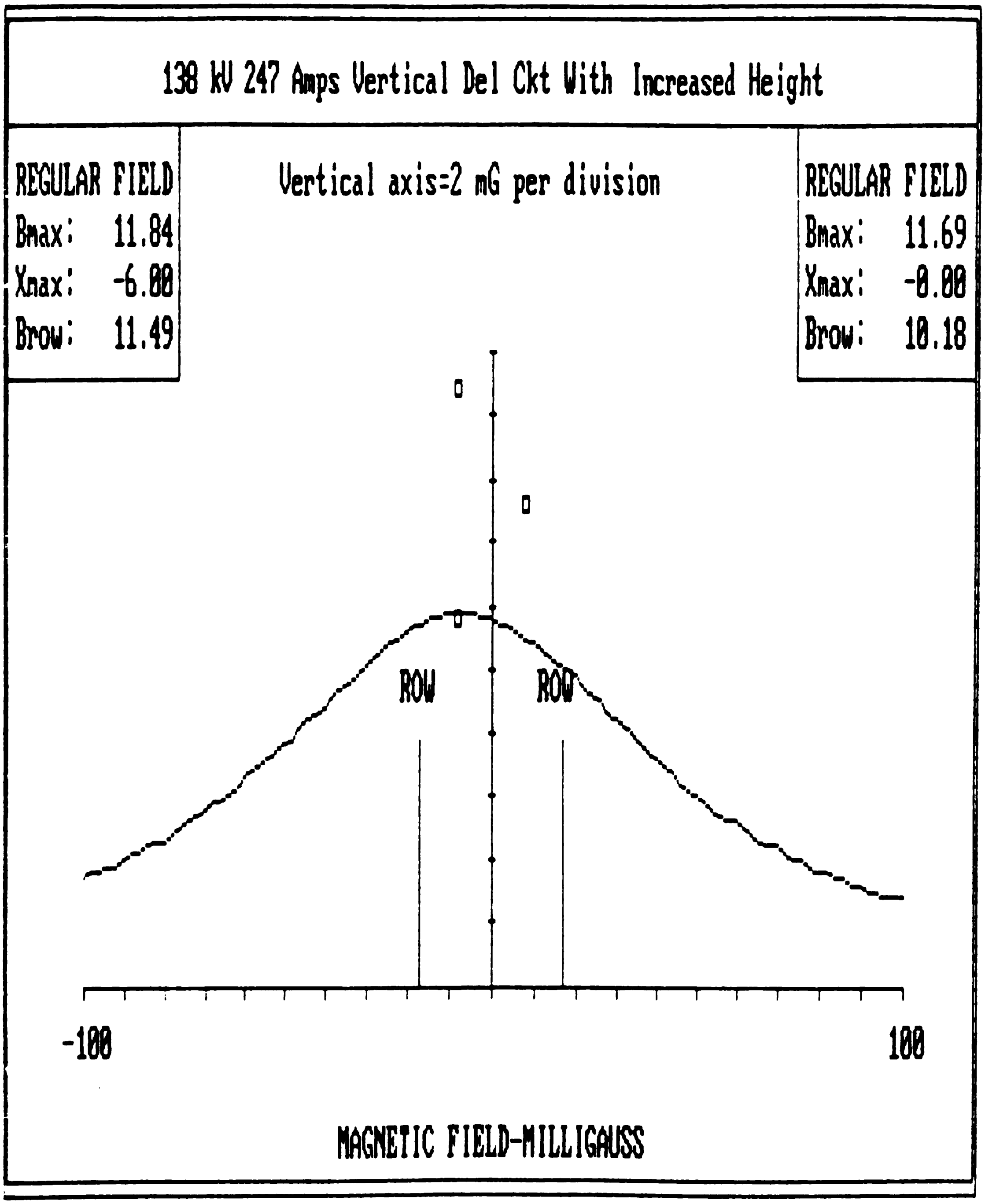


Figure 19. Magnetic field of case 2.2 at typical load current of 247 amps, when the transmission circuit is 20 feet higher than the original one.

CASE 2.3: Increased Height with a Degaussing Circuit

The cases of an increased elevation of the transmission circuit and of the insertion of a Degaussing circuit are combined. This would result in a significant magnetic field intensity reduction, especially at the right-of-way. Figure 20 shows the reduced field due only to an increase of 20 ft in the elevation of the circuit (upper curve), and the reduced field due to the combination of using a higher circuit with two energized degaussing wires (lower curve). The field intensity has decreased from 19.80 mG to 5.71 mG and from 25.33 mG to 5.96 mG at the right edge and the left edge of the ROW, respectively. The results are summarized in table 12 for the right edge of the ROW.

Table 12. *Magnetic field reduction of case study 2.3.*

Right Edge	Normal Field (mG)	Reduced Field (mG)	Percentage Decrease(%)
B at The ROW	19.80	5.71	71.16 %
B-maximum	26.60	6.14	76.92 %

The required currents and locations of the B-field reduction wires are given by TLField,and summarized in Table 13.

Table 13. *Degaussing circuit specification for case study 2.3.*

Conductor No	X (ft)	Y (ft)	Current (Amps)	Phase Angle (Degrees)
5	-12.00	+82.00	111.15	+120.00
6	-12.00	+50.00	111.15	-60.00

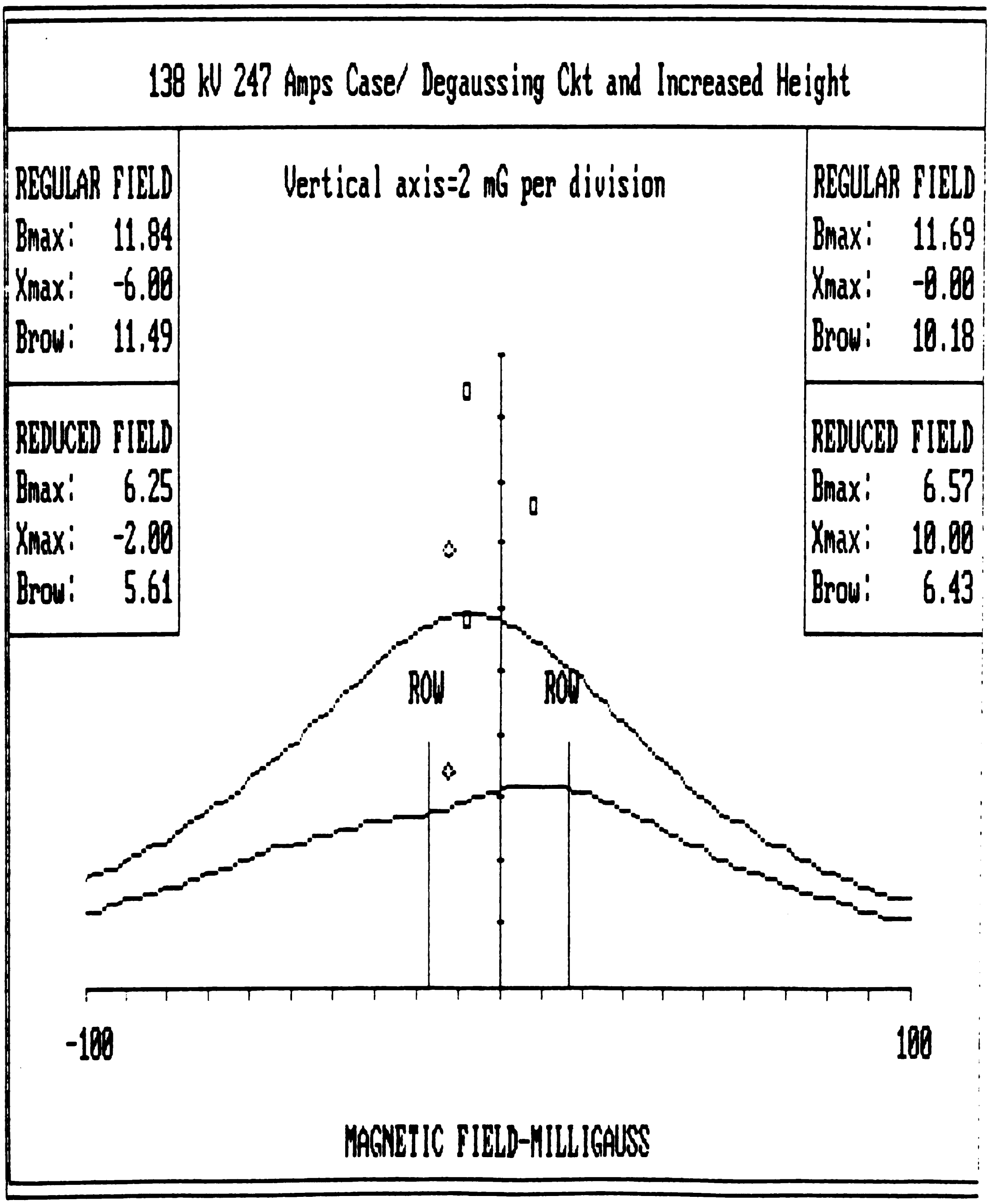


Figure 20. Magnetic field of case 2.3 at typical load current of 247 amps. The circuit is modified by the insertion of a degaussing circuit, and by increasing its height.

CHAPTER NINE

CONCLUSION

Power frequency electromagnetic fields emitted by transmission lines and electric equipment have been suggested as a possible cause for long term effects on health. Studies of the association between exposure from installations transmitting or generating electric power and the occurrence of cancer cases such as childhood cancer and leukemia among electric workers have been reviewed. Some epidemiologic studies have indicated statistical correlation but none that has been verified by scientific experiments.

The role of the geometrical configuration of transmission lines in magnetic field reduction has been investigated.Various other techniques for magnetic field control of existing transmission lines have been suggested. Two case studies from existing transmission systems have been studied for a magnetic field reduction objectives.

The conclusions drawn from this study are:

1) The effects of low frequency magnetic field exposure on human health have not been confirmed. Epidemiological studies were subject to two major weaknesses: insufficiency of data on actual field intensities and absence of exposure assessment

guidelines (based on health effects research) to classify individual cases.

2) The limitation of magnetic field exposure is only a precautionary measure, defendable until scientific results are available.

3) Line geometrical configuration of transmission lines is a critical factor in minimizing magnetic field strength at the edges of the right-of-way (ROW).

i) Low-field, low reactance reverse-phase configuration is a feasible magnetic field reduction technique, for new lines or when upgrading existing circuits for more capacity.

i) Delta configurations perform some field cancellation, with the advantage of using a narrower ROW.

iii) Underground transmission lines, due to their close conductor proximity, provide a significant field reduction. However their high cost makes their use limited.

4) Using higher circuits (conductors farther above the local surface) is very effective in reducing the magnetic field intensity at the edges of the ROW. Higher circuits increase tower costs and may increase aesthetic sensitivity to their appearance.

5) A degaussing circuit is a two conductor circuit inserted nearby and parallel to the phase conductors. When these conductors are energized by the appropriate currents and phase angles specified by a simulation program, a significant field reduction results. The specified currents are usually difficult and costly to provide, besides, the line currents vary instantaneously with the load.

This problem of EMF will receive media, industry, government and medical and scientific attention until the health effect issue is understood. This thesis is an effort to explain this complex inter disciplinary problem and to suggest an amelioration procedure for transmission-induced magnetic fields.

APPENDIX A

CALCULATION OF THE MAXIMUM MAGNETIC FIELD OF TRANSMISSION LINES

APPENDIX A

CALCULATION OF MAXIMUM MAGNETIC FIELD

The maximum phasor component of the magnetic field in a point in space is represented by the magnitude and direction of the major semi-axis of the field ellipse. The ellipse axes correspond to the zero rate of change of the field magnitude with respect to angle in space and with respect to time. The angle derivation starts with the vertical and horizontal magnetic field components expressed in Equations (5.8) and (5.9).

The magnitude, B_α, of the component of the field along a direction defined by an angle, α, with respect to the horizontal is expressed by Equation (A.1):

$$(B_\alpha)^2 = (B_{ry}\sin\alpha + B_{rx}\cos\alpha)^2 + (B_{iy}\sin\alpha + B_{ix}\cos\alpha)^2 \qquad (A.1)$$

The angles corresponding to maximum and minimum fields are determined by setting the derivative of expression (A.1) with respect to the angle α equal to zero:

$$\frac{d(B_\alpha)^2}{d\alpha} = 0 \qquad (A.2)$$

Equation (A.2) may be written as a quadratic equation with $\tan\alpha$ as the unknown variable:

$$\tan^2\alpha\,(\dot{B}_{ry} \bullet B_{rx} + B_{iy} \bullet B_{ix}) + \tan\alpha\,(-B^2{}_{iy} + B^2_{ix} - B^2_{ry} + B^2{}_{rx})$$

$$-(\dot{B}_{ry} \bullet B_{rx} + B_{iy} \bullet B_{ix}) \qquad (A.3)$$

Equation (A.3) has two solutions corresponding to the major and minor axes of the ellipse. The magnitude of the semi-axes is evaluated by substituting the angles in equation (A.1).

The time derivation starts with the vertical and horizontal components expressed as vectors with instantaneous values varying in time:

$$\vec{B}_x = H\cos(\omega t + \theta)\ .\ \vec{u}_x \qquad (A.4)$$

and

$$\vec{B}_y = V\cos(\omega t + \phi).\ \vec{u}_y \qquad (A.5)$$

Where:

H is the maximum horizontal component

$$H^2 = B_{rx}{}^2 + B_{ix}{}^2$$

θ is the phase angle of the horizontal component

$$V^2 = B_{ry}{}^2 + B_{iy}{}^2$$

and ϕ is the phase angle of the vertical component

$$\phi = \arctan\left(\frac{B_{iy}}{B_{ry}}\right)$$

The instantaneous field is a vector in space expressed by

$$\vec{B} = \vec{B}_x + \vec{B}_y \qquad (A.6)$$

The square of instantaneous field magnitude is

$$B^2 = H^2 \cos^2(\omega t + \theta) + V^2 \cos^2(\omega t + \phi) \qquad (A.7)$$

The field is maximum or minimum when

$$\frac{dB^2}{dt} = 0 \qquad (A.8)$$

The solution of Equation(A.8) is given

$$\tan(2\omega t) = -\frac{H^2 \sin 2\theta + V^2 \sin 2\phi}{H^2 \sin 2\phi + V^2 \cos 2\phi} \qquad (A.9)$$

If ωt_1 is a solution of Equation (A.9), then the other solutions are

$$\omega t_1 = \omega t_1 + (m-1)\,\pi / 2 \qquad (A.10)$$

Equation (A.10) has four solutions for m= 1, 2, 3, and 4. The pair t_1,t_3 (and t_3, t_4), corresponds to two directions of the same axis. The magnitude of the semi-axes are evaluated by substituting these terms back into Equation (A.7).

APPENDIX B

TLFIELD MAGNETIC FIELD CALCULATIONS FOR A 13.2 KV LINE USING A FIELD DEGAUSSING CIRCUIT TO MINIMIZE THE MAGNETIC FIELD AT THE RIGHT-OF-WAY

LINE INPUT DATA
SHIELD WIRE DESCRIPTION

Case Title: 13.2 kV 250 Amps Delta Using a Field Degaussing CKT.

User: Khadija Benkilani

What height (ft) above ground for calculations? 3.00

No. of shield wires <10: 0

LINE INPUT DATA
PHASE CONDUCTOR DESCRIPTION

No. of phases <25: 3

Cond. No.	Phase Coordinates X(ft)	Y(ft)	Subconds. Per Bundle	Cond. Diam. (in)	Bundle Diam. (in)	Phase-Phase kV	Angle Degrees
1	-3.50	37.00	1	1.40	1.40	13.20	0.0
2	0.00	38.00	1	1.40	1.40	13.20	120.0
3	3.50	37.00	1	1.40	1.40	13.20	240.0

What soil resistivity, ohm-meters? 100.00

LINE MAGNETIC FIELD ASSESSMENT

Cond. No.	Coordinates X(ft)	Y(ft)	Current Amps.	Degrees
1	-3.50	37.00	250.0	0.00
2	0.00	38.00	250.0	120.00
3	3.50	37.00	250.0	240.00

LINE INPUT DATA
LOCATION OF MAGNETIC FIELD DEGAUSSING CIRCUIT

You are permitted to insert a two-conductor magnetic field degaussing circuit nearby and parallel to the phase conductors to reduce the magnetic fields at the edges of the right-of-way or beyond. See your users manual for details.

Do you wish to insert a degaussing circuit (Y or N)? Y

What is degaussing wire diameter (in)? 1.00

Degauss Wire No.	Wire X Coord. (ft)	Wire Y Coord.(ft)	Cancellation X Coord.(ft)
4	-3.50	35.00	-17.00
5	3.50	35.00	17.00

REQUIRED CURRENTS AND LOCATIONS FOR H-FIELD REDUCTION CONDUCTORS

Case: 13.2 kV 250 Amps Delta Using a Field Degaussing CKT.

Conductor No.	X(ft)	Y(ft)	Current (amps)	Phase Angle (Degrees)
4	-3.50	+35.00	187.50	+210.00
5	+3.50	+35.00	187.50	+30.00

Aug 15 1991 ELECTRIC AND MAGNETIC FIELD PLOTTING SPECIFICATIONS

Input leftmost x-coordinate (ft) for field plot:	-100.0
Input total horizontal distance (ft) to be plotted:	200.0
What is x-coordinate (ft) at left edge of right-of-way?	-17.0
What is x-coordinate (ft) at right edge of right-of-way?	17.0
What is x-coordinate (ft) of the vertical scale?	0.0

13.2 kV 250 Amps Delta Using a Field Degaussing CKT.
Calculated Regular Magnetic Field Profile

X(ft)	mG	X(ft)	mG	X(ft)	mG	X(ft)	mG	X(ft)	mG
-100	0.9	-60	2.1	-20	6.4	20	6.4	60	2.1
-98	0.9	-58	2.2	-18	6.7	22	6.0	62	2.0
-96	1.0	-56	2.3	-16	7.0	24	5.7	64	1.9
-94	1.0	-54	2.4	-14	7.3	26	5.4	66	1.8
-92	1.0	-52	2.6	-12	7.6	28	5.1	68	1.7
-90	1.1	-50	2.7	-10	7.9	30	4.8	70	1.6
-88	1.1	-48	2.9	-8	8.1	32	4.6	72	1.6
-86	1.2	-46	3.0	-6	8.3	34	4.3	74	1.5
-84	1.2	-44	3.2	-4	8.4	36	4.1	76	1.4
-82	1.3	-42	3.4	-2	8.5	38	3.8	78	1.4
-80	1.3	-40	3.6	0	8.5	40	3.6	80	1.3
-78	1.4	-38	3.8	2	8.5	42	3.4	82	1.3
-76	1.4	-36	4.1	4	8.4	44	3.2	84	1.2
-74	1.5	-34	4.3	6	8.3	46	3.0	86	1.2
-72	1.6	-32	4.6	8	8.1	48	2.9	88	1.1
-70	1.6	-30	4.8	10	7.9	50	2.7	90	1.1
-68	1.7	-28	5.1	12	7.6	52	2.6	92	1.0
-66	1.8	-26	5.4	14	7.3	54	2.4	94	1.0
-64	1.9	-24	5.7	16	7.0	56	2.3	96	1.0
-62	2.0	-22	6.0	18	6.7	58	2.2	98	0.9

13.2 kV 250 Amps Delta Using a Field Degaussing CKT.
Calculated Reduced Magnetic Field Profile

X(ft)	mG	X(ft)	mG	X(ft)	mG	X(ft)	mG	X(ft)	mG
-100	0.1	-60	0.3	-20	0.8	20	0.8	60	0.3
-98	0.1	-58	0.3	-18	0.8	22	0.8	62	0.3
-96	0.2	-56	0.4	-16	0.9	24	0.8	64	0.3
-94	0.2	-54	0.4	-14	0.9	26	0.7	66	0.3
-92	0.2	-52	0.4	-12	0.9	28	0.7	68	0.3
-90	0.2	-50	0.4	-10	0.9	30	0.7	70	0.3
-88	0.2	-48	0.4	-8	0.9	32	0.6	72	0.2
-86	0.2	-46	0.5	-6	0.9	34	0.6	74	0.2
-84	0.2	-44	0.5	-4	0.9	36	0.6	76	0.2
-82	0.2	-42	0.5	-2	0.9	38	0.6	78	0.2
-80	0.2	-40	0.5	0	0.9	40	0.5	80	0.2
-78	0.2	-38	0.6	2	0.9	42	0.5	82	0.2
-76	0.2	-36	0.6	4	0.9	44	0.5	84	0.2
-74	0.2	-34	0.6	6	0.9	46	0.5	86	0.2
-72	0.2	-32	0.6	8	0.9	48	0.4	88	0.2
-70	0.3	-30	0.7	10	0.9	50	0.4	90	0.2
-68	0.3	-28	0.7	12	0.9	52	0.4	92	0.2
-66	0.3	-26	0.7	14	0.9	54	0.4	94	0.2
-64	0.3	-24	0.8	16	0.9	56	0.4	96	0.2
-62	0.3	-22	0.8	18	0.8	58	0.3	98	0.1

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