Magnetic Field Management in Underground Cables

by

Firoz Ahmad

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

June, 1996

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UMI Number: 1381993

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA

COLLEGE OF GRADUATE STUDIES

This thesis, written by **FIROZ AHMAD** *under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements for the degree of* **MASTER OF SCIENCE** *in* **ELECTRICAL ENGINEERING**.

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Dedicated to....

my parents

Acknowledgment

First and foremost, I thank the Almighty, who gave me the opportunity, courage and patience to carry out this work.

Acknowledgement is due to King Fahd University of Petroleum & Minerals for providing support to this work.

I am indebted to my thesis Chairman, Dr. Ahmed S. Farag for his kind help and advice. I acknowledge him for his valuable time, encouragement and guidance. I thank my thesis co-Chairman Dr. J.M. Bakhashwain for his continuous support and encouragement. My thanks are also due to the committee members, Dr. Mahmoud M. Dawoud and Dr. I.O. Habiballah for their comments and critical review of the work. I also wish to thank the department chairman, Dr. Samir Al-Baiyat, and other faculty members for their cooperation.

My sincere appreciation to my many friends for their wonderful support and company which made my stay on campus eminently enjoyable.

Finally a word of grateful thanks to my parents, who never shackled my freedom and gave me unstinted support and unlimited discretion in pursuing what I thought best.

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THESIS ABSTRACT

Name: FIROZ AHMAD

Title: MAGNETIC FIELD MANAGEMENT IN UNDERGROUND CABLES
Degree: MASTER OF SCIENCE

Major Field: ELECTRICAL ENGINEERING

Date of Degree: JUNE 1996

Adverse health effects due to magnetic field is a matter of great concern and very widely debated in recent years. Managing these high fields is a challenge to researchers. One of the important source of magnetic field is power cable and is addressed in this thesis work. Different management techniques have been studied in detail. Judicious placement of cable phases in multiconductor lines is a powerful technique to reduce the field and has been implemented by computer modelling and simulations. Implementation has been done for both single phase and three phase cables for a number of cases and cable sizes. Increasing the burial depth of cables helps more in reducing the peak value which is near the center line of conductors. Some of the new designs for two, three and four cables per phase has been proposed from magnetic field perspective and other considerations. Passive shielding scheme has been implemented and is found to be the most powerful of all of them. The reduction obtained is sometimes as high as 97-98%. This scheme is a costly one and as such there has to be a trade-off between the cost and the level of reduction desired. Shielding the source and shileding the subject are two different things. Both of them have been discussed and implemented in this work. It is also acknowledged that employing the high cost schemes is not practical at this stage and not likely to be adopted till there is a definite conclusion about the health hazards due to these high fields.

King Fahd University of Petroleum and Minerals, Dhahran.
June 1996

خلاصــــة الرســـــالة

الأســـــــم : فـيروز أحمـد

عنوان الرسالة : التحكم فـي المجـالات المغناطيسـية فـي حالـة الكـابلات الأرضيـة

التخصـــص : الهندسـة الكهربائيـة

تاريخ الشهادة : محـرم ١٤١٧هـ

إن تـأثيرات الصحـة المعاكسـة نتيجـة المجـال المغناطيسـي أمـر مهـم للغايـة وأصبـح موضوعـا للمناقشـة عالميـا فـي السـنوات الأخـيرة ، وإن عمليـة التحكـم فـي هـذه المجـالات العالميـة أصبحت تتحـدى الباحثين . أحد أهـم المصـادر للمجـال المغناطيسـي هـو الكوابـل والتـي هـي موضـوع هـذا البحث . إن عمليـة وضـع فـازات الكـابل ذات الخطـوط المتعددة بطريقـة حكيمـة تسـاعد علـى التقليـل مـن المجـال المنبثـق وقـد طبقت هـذه الطريقـة بواسطة نمـاذج ومحاكـات الحاسـوب .

كمـا طبقت هـذه الطريقـة للكوابـل ذات الفـاز والثلاثـة فـازات وذلـك للعديـد مـن الحـالات والأحجـام المختلفـة للكـابلات . كمـا أن عمليـة زيـادة عمق الحفر للكـابل تسـاعد فـي تقليـل قيمـة المجـال الأعلـى والـذي عـادة مـا يكـون عنـد وسـط الخـط للموصـلات . لقـد اقـترحت بعـض حـالات التصميـم الجديـدة لأثنـان وثلاثـة وأربعـة كـابلات للفـاز وذلـك مـن وجهـة نظـر المجـال المغناطيسـي كمـا أن عمليـة الحمايـة طبقت ووجـد أنهـا الأفضـل مـن الجميـع . حيـث أن التقليـل للمجـال قـد يصـل أحيانـا إلـى حوالـي ٩٧-٩٨٪ .

لكـن هـذه الطريقـة باهظـة التكـاليف وبالتـالي فـإن هنـاك مسـاومة بيـن ارتفـاع التكـاليف للحصـول علـى مجـال أقـل . إن حمايـة المصـدر وحمايـة الشـيء أمـران مختلفـات وكـلا هذيـن الأمريـن نوقشـا فـي هـذه الرسـالة . كمـا أن مـن المعـروف أن تطبيـق الطـرق العاليـة ليـس عمليـا فـي هـذه المرحلـة ومستبعد تطبيقـه إلا فـي حالـة المخـاطر الصحيـة الناجمـة مـن التعرض لهـذه المجـالات العاليـة .

درجة الماجستير في الهندسة الكهربائية
جامعـــة الملك فهـــد للبتـــرول والمعـــادن
الظهران – المملكة العربية السعودية

Chapter 1

Introduction

1.1 General Background

Concern about the electromagnetic field biological effects first began in the mid 1960's in the Western part of the former Soviet Union when the workers in the transmission switchyards complained of appetite loss, fatigue, headaches, insomnia, and reduced sexual drive. In the United States the concern began in 1974 during addressing of a proposal by New York State utilities to build two 765-kV transmission lines.

A number of epidemiologic studies have been done since 1979 to identify the adverse health effects on human beings such as childhood leukemia, male breast cancer, as well as brain tumor due to the exposure to electromagnetic fields [1-12]. Although most of the health effects concern has centered on fields generated by power lines, many people may receive more exposure from indoor wiring and appliances in the home or workplace. Field exposure is thus an inevitable consequence of living in a society that uses electricity.

Much of the early work investigated whether high-voltage electric fields produce biological effects in plants and animals. The focus then was on electric fields from transmission lines because a number of such lines were being contested, in part, on the grounds of health concerns. Those studies demonstrated that effects do occur but do not appear to be harmful. With this groundwork established, Electric Power Research Institute's (EPRI) research emphasis is now moving to address concerns of a link between cancer and magnetic fields from residential exposure (including that from neighborhood distribution lines) or from occupational exposure. Electric fields are easily blocked by vegetation, buildings, fences, and other objects and has notbeen much of a concern. They can also be virtually eliminated by grounded shield wires or screens in direct contact with the earth. Buried power lines produce almost no electric fields above ground. On the other hand magnetic fields pass easily through most objects, including buildings, earth, and people [1].

Since the publication of results of the epidemiologic study done by Nancy Wertheimer and Ed Leeper in 1979 [2] there is an increased public concern about the possible health hazards due to the exposure to electromagnetic field. Research study by Wertheimer have indicated that cancer and other health problems may be linked to a person's long term exposure to low frequency electromagnetic fields. But while study after study has investigated this possibility, anomalous results make a clear conclusion elusive. Little as yet is known about how such a health link might operate or what aspects of electromagnetic fields might cause these problems.

Glimpses of answers have surfaced in several recent investigations, some of which were epidemiological studies tracking large groups of people, their exposure to fields, and their cancer rates, while others involved laboratory research on animals and living tissue. Meanwhile some risk analysis experts counsel " prudent avoidance" - taking simple steps to reduce the exposure to electromagnetic fields on daily life without going out on an economic limb.

It is this concern which shoulders an extra responsibility on the power system engineers to identify the sources, quantify the associated magnetic field levels due to these sources and find a way to reduce the fields or manage it in such a way that the people are not exposed to it. One of the prime source of magnetic field in power systems is the transmission and distribution cables and it is with this sense of responsibility that this study is being done.

1.2 Epidemiological Studies

The hypothesis linking magnetic fields to cancer now rests entirely on correlations from epidemiologic studies. Unlike laboratory studies, which develop hard cause-effect relationships from experimental evidence, epidemiology is a science of association, relying on statistics to detect connections between potentially harmful agents and patterns of disease in human populations. Studies are classified as Residential and Occupational and are discussed in brief here.

1.2.1 Residential studies

The first suggestion that electromagnetic fields at extremely low frequencies (0 - 300 Hz) were linked to cancer came in 1979, when Nancy Wertheimer and Ed Leeper published the results of a study of childhood deaths from cancer in Denver, Colorado [2]. After determining power lines as a possible factor, the researchers coded the lines outside the homes for high, medium, or low current flow, (and postulated that these ratings corresponded) on an average, to high, medium, or low magnetic field exposure inside the homes. Wertheimer and Leeper devised a "wire code" that led them to label the houses as high, medium, or low field just by looking at the size and location of power lines in the area. They found that children living in "high wire code" houses were about twice as likely to develop leukemia as those in "low wire code" houses.

However, this study was said to be flawed. The critics argued that the researchers had been inaccurate in their use of types and layout of transmission and distribution lines - so-called wire codes. It was also argued that they failed to rule out confounding factors, such as air pollution and housing density, that are unrelated to power lines but might have contributed to the cancer.

A similar study was conducted in Rhode Island [3] in the following year and when no evidence of links to cancer was found many researchers dismissed the Wertheimer -Leeper findings .

The work done by Nancy Wertheimer surfaced again in the wake of a second study of childhood cancer in Denver, completed in 1986 as part of the utility funded New York State Power Lines Project. This study expanded on Wertheimer and Leeper's work and improved some of the weaknesses in the original study's design. This study expanded on Wertheimer and Leeper's work and improved some of the weaknesses in the original study's design. This work was conducted by David Savitz, Howard Wachtel, and Frank Barnes [4], and they had used a wire coding system similar to that developed by Wertheimer and Leeper but also used point measurements of magnetic fields in the subject's homes. In this study the coding was blind, and it used a set of children entirely different from those in the Wetheimer and Leeper study. Like first study, the second study did find a modest statistical correlation between childhood cancer and the proximity of their homes to high current configuration lines.

Research has also continued at the University of Southern California, in Los Angeles, and a report in 1991 from the school uncovered apparent links between childhood leukemia and household wiring configurations and between leukemia and the use of black-and-white television sets and electric hair dryers; but no statistically significant link was evident after monitoring of magnetic field strength over a period of time [5, 6].

Meanwhile, a 1993 Finnish study of children living within 500 meters of overhead power lines gave no statistically significant rise in susceptibility to leukemia and lymphoma, although it did report a slight excess of nervous system tumors in boys exposed to magnetic fields above $2mG$ [6, 7, 8].

A 1992 Swedish study, published after the Finnish one, added to the evidence of a link. It showed triple the risk of contracting leukemia for children who lived in houses with fields of at least $2mG$, compared with those living amid weaker fields (down to $1mG$), and quadruple the risk if the fields were $4mG$ and up. The Swedish researchers calculated average field strength for one full year from detailed utility records. More recently, a 1993 Danish study noted a significant association between the sum total of all major types of childhood cancer and the children's exposure to magnetic fields higher than $4mG$ [6, 7, 8].

During the same period, several studies have been conducted and results must be interpreted cautiously because the number of cases are limited [9, 10, 11, 12].

1.2.2 Occupational studies

A number of occupational studies have relied on job titles alone as an indication of the exposure levels in various professions. This approach has obvious drawbacks as it clusters individuals who may in fact experience widely different exposure. Electrical engineers, for example, have been assumed in some studies to experience uniformly high exposure despite the fact that some of them work near equipment that produces strong fields, while others work in offices far from such equipment.

Savitz and Calle surveyed the epidemiology on workers in so called electrical occupations, such as electricians, linemen, and motion picture projectionists [1].Overall, the research in this area suggests that these professions have a slightly elevated risk of leukemia and brain cancer. In the year 1982 a report by Samuel Milham Jr., an epidemiologist suggested that the death due tc leukemia seem to be elevated in 10 out of 11 occupations that involves exposure to electromagnetic fields [6]. Some other investigations such as the one done on the workers in aluminum plant found that workers died from leukemia and lymphoma at five times the expected rate [6]. Another study found that the telephone cable workers suffer from leukemia seven times more than the other telephone company employees; a University of Southern California study suggested that electrical workers were 20-30 percent more likely to develop leukemia than other phone workers [6].

Another study done by G.Theriault et al, [11] in 1993 gathered 10,000 worker-days of measurement done on 223,000 utility workers of Ontario Hydro, Hydro-Quebec, and Electricite de France. They found a 3.15 times increase in risk for acute myeloid leukemia and a 12.0 risk increase in a certain form of brain cancer among the most exposed 10 percent of the population. A Swedish study showed three times the likelihood of chronic lymphocytic leukemia for the exposed group while the one by Southern California Edison Co., showed no increase in risk for exposed workers [6].

Some other studies indicated that the breast cancer might be a more serious thing to look at as the number of deaths due to it, is very high. D.A.Savitz et al., [4] suggested that the female electrical workers had a 40 percent higher mortality rate from breast cancer than women in non-electrical jobs. Another study conducted at the Fred Hutchinson Cancer Research Center, Seattle, Washington forecasts a sixfold increase an the rate of breast cancer among male telephone linemen, electricians, and electrical power workers [6].

In the meantime, with the current knowledge, the policy of avioding exposure to high magnetic field without incurring much of a cost proposed by Granger Morgan appears to be the most widely accepted [12]. The fact that evidence exists suggesting enough of a potential health problem means finding low cost and no cost schemes to reduce the field levels. Still, there are enough unknowns about the magnitude of the risk and which aspects of the fields cause the risk that spending millions to move power lines may not seem wise, either. In other words till it is established that magnetic fields causes adverse health affects trying costly management techniques will not be taken seriously.

1.3 Scope of Work

1.3.1 Motivation

The environmental effects of electric fields have been studied since the early 1970's, but the effects of magnetic fields gained publicity only during the last few years as a result of the several epidemiological studies. There is no doubt, however, that many people are concerned about the magnetic field effects of power frequency electric currents associated with AC transmision and distribution underground cables. While health studies are in progress, it appears desirable to conduct parallel technical studies related to the magnetic field management that serve as a guideline to the utilities in practical implementation in occupational areas.

Magnetic field management techniques for cables being a recent area of research has not received much of an attention from researchers and utility engineers. Application of some of these techniques to multi conductor underground lines which are very much in use so as to reduce the field levels have not been done so far and they are very much a source of concern because of high currents which they are suuposed to carry. Attempt has been made to see the reduction over a distance by the application of some of the management techniques for the case of multiconductor underground lines.

1.3.2 Thesis organization

This thesis is divided into six chapters. In Chapter 1, the historical background and different epidemiological studies done on the adverse health effect due to magnetic field are briefly outlined [1-12]. Chapter 2 contains some of the basic magnetic field principles, factors affecting the magnetic field in an Underground transmission and distribution cables and an example showing how the magnetic fields are calculated for a cable. In Chapter 3, different management techniques of magnetic field as applied to a cable are discussed. Due importance has been given to the Shielding technique which is very effective. Chapter 4 contains the implementation of some of the management schemes for multiconductor lines. Simulation results are tabulated and a large number of plots are also incorporated in this chapter. Configuration of the cable phases, effect of depth of burial and some new designs are the highlight of this chapter. In Chapter 5, the implementation of the shielding technique is documented. Finally, in Chapter 6, the conclusions and some of the recommendations for the future work in this area are outlined.

1.3.3 Main contributions

- Simulation for the EPRI recommended cable designs for multi conductor lines.
- Configuration of the phases for these lines for standard arrangements so as to give minimal magnetic field values which has not been done before.
- Study the effect of depth on field values and comment on the location where this is most effective .
- Development of some new designs which reduces the field levels as well gives symmetrical and compact network.
- Implementation of Passive shielding schemes and comparison between the shielded and the unshielded values . A very high reduction is obtained though the scheme is quite costly.

Chapter 2

Magnetic Field Principles

There are several types of force fields in nature. Two of these are important to the power engineer: electric and magnetic fields. The magnetic field is the focus of the work at hand, and the electric field is similar in many respects to the magnetic field, and is more familiar to the utility engineer.

Electric fields are created by the presence of electric charges while magnetic fields are created by the movement of these charges (electric currents). When the rate of change (frequency) of these fields is sufficiently low, as in the case of power system fields, electric and magnetic fields can be separated into electric (related to voltages) and magnetic (related to current) fields and the word electromagnetic should be defined as *Electric and Magnetic Fields*, as opposed to *Electromagnetic* which implies that electric and magnetic fields are coupled together as in high frequency radiating fields.

2.1 The Magnetic Field

The magnetic field is defined by the magnitude and direction of the force exerted on a moving charge. If an electric charge is moving into a magnetic field, or if a field moves past the charge, the charge will be subjected to a force. If one Coulomb of charge moves at a velocity of one meter per second, perpendicular to a magnetic flux density of one tesla, it will be subjected to a unit force of one Newton, in a direction orthogonal to both the direction of the charge motion and the direction of the magnetic field.

The magnetic field or the magnetic flux density is almost universally represented by the symbol B. This is also expressed in terms of flux per unit area.

$$\phi = BA \tag{2.1}$$

The unit of B is *weber/meter*^{2}, or *tesla*(T) in MKS unit and *gauss*(G) (the unit milligauss is often used) in CGS system of units. It is important to note here that there is also a term known as " magnetic field strength", usually denoted by the letter (H), and is measured in ampere per meter (A/m). B and H are related to each other by the following relationship,

$$B = \mu H \tag{2.2}$$

where, μ is known as the permeability of the medium and gives an indication of how that material affects the magnetic flux density that penetrates it [13].

The quantity B, being a vector, has three spatial components: B_x, B_y, and B_z

as shown in Fig.2.1.

B can be produced by a DC current and, therefore, be constant in time (such as earth's magnetic field), or it can be produced by AC current. In an AC field of a particular frequency, all three spatial components oscillate at that frequency (and can be represented as phasors). However, the overall field can be composed of the superposition of several fields with different frequencies (harmonics). For most purpose, the power engineer is primarily concerned with the magnetic field generated by the power frequency 50/60 Hz. The contribution due to the harmonics are beyond the scope of this work and are not discussed here.

In a 60Hz field the three spatial components are scalar quantities sinusoidally oscillating at 60 Hz. Fig.2.2 illustrates how one of these components might look when plotted against time. The other two components would look similar. Each component has its own peak and rms value, and phase [14].

Also, each of the three components can be represented as a phasor, as illustrated in Fig.2.3. The length of the phasor B_x represents the rms magnitude of the magnetic field (or peak magnitude, depending on the convention used), and the angle that the phasor makes with the real axis represents its phase with respect to some reference. The projection of the phasor onto the real axis is called the real part ($B_{x,r}$), and the projection onto the imaginary axis is called the imaginary part ($B_{x,i}$). Application of the Pythagorean theorem to the phasor shown in Fig.2.3 gives the magnitudes of the three components as follows,

$$B_x = \sqrt{B_{x,r}^2 + B_{x,i}^2}; B_y = \sqrt{B_{y,r}^2 + B_{y,i}^2}; B_z = \sqrt{B_{z,r}^2 + B_{z,i}^2} \tag{2.3}$$

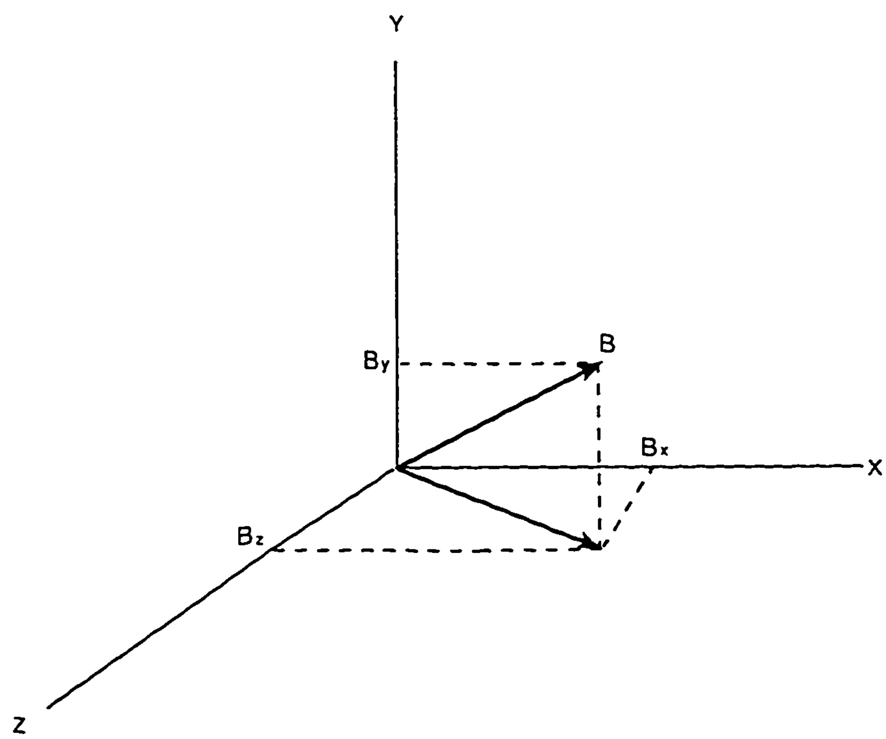


Figure 2.1: A magnetic field density vector, B, and its three spatial components, B_x, B_y, B_z

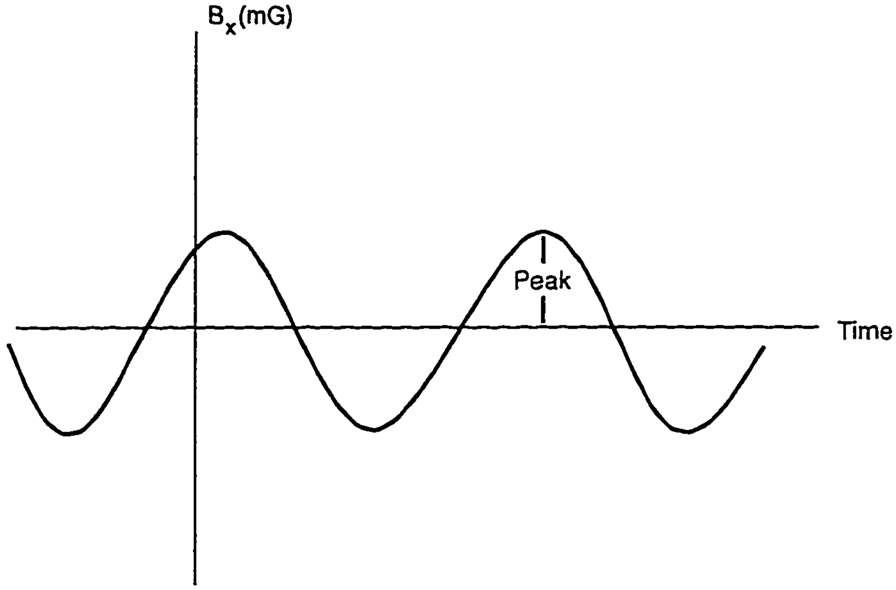


Figure 2.2: Illustration of how one of the spatial components of B may vary with time.

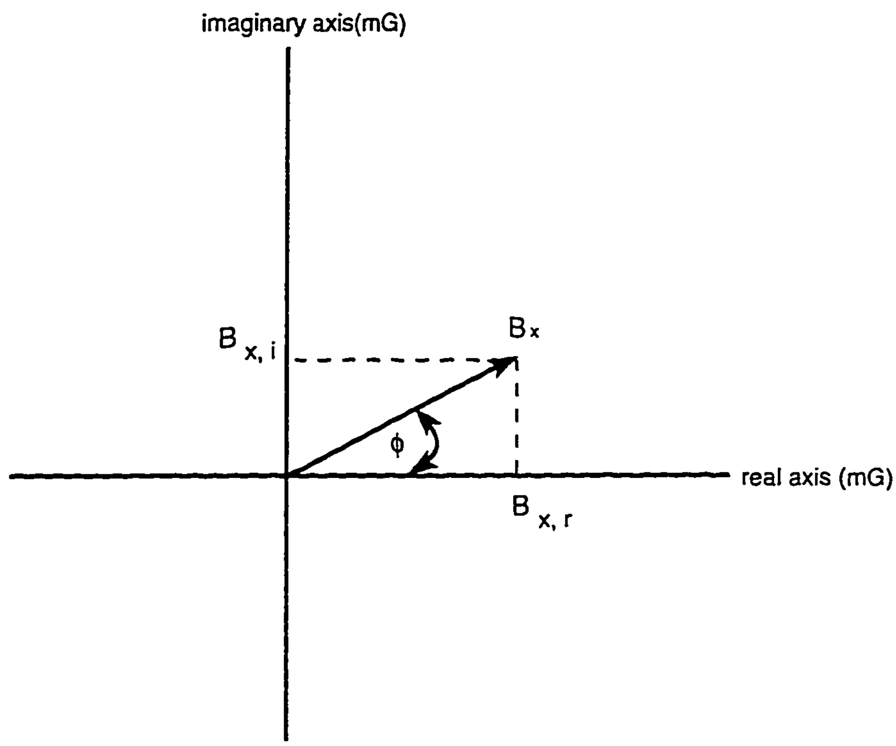


Figure 2.3: Phasor representation of the x-component of magnetic field.

Further, it can be shown that the resultant magnetic field is given by,

$$B_{resultant} = \sqrt{B_x^2 + B_y^2 + B_z^2} \tag{2.4}$$

2.2 Factors Affecting the Magnetic Field

There are numerous factors which affect the values of the magnetic fields produced by underground transmission cables (which is of interest in this thesis work). These factors may be grouped into the following general areas [15, 16, 17]:

- System parameters; such as current magnitude and phase balance, and system grounding,
- Cable installation parameters; such as depth of burial, installation configuration, and relative placement of the cable phases where there is more than one circuit,
- Cable construction parameters; primarily shield/sheath resistance and type of material for non-pipe-type cables, and
- External factors such as the presence of nearby underground conductors or sources of current which may flow on the cable sheath/shield or ground continuity conductor.

(I) System parameters

The most obvious parameters which affect the magnitude of the magnetic field in the vicinity of an underground transmission line is the magnitude of the current in the phase conductors. The material of the cable and the soil surrounding the cable have a constant magnetic permeability which makes the magnetic field values at a given locations a linear function of the conductors phase currents. Zero sequence currents flowing in transmission cable circuits have significant effects on magnetic field magnitudes and how rapidly it decreases with the distance from the center of the line of the circuit. The magnetic field magnitudes for positive sequence currents decreases approximately as one over the distance squared from the center line of the circuit while magnitudes for zero sequence current decreases approximately with the reciprocal of the distance as illustrated in Fig.2.4 [18]. The manner in which the cable system is grounded also has an effect on the magnetic field values due to the fact that induced currents in the cable shield/sheath grounding alternatives on the magnetic field produced by the cable system.

Multi-point grounding

It is the simplest type of shield/sheath grounding method and results in the lowest shield/sheath voltage with respect to ground; however, it results in appreciable induced shield/sheath currents and losses. The current carrying capacity of a cable circuit with multi-point grounding may be reduced by 60 percentage or more compared to a cable with single point grounding or cross- bonded shields/sheaths. The induced shield/sheath current has another effect as it tends to reduce the magnetic field produced by the phase currents due to the fact that this induced current is close to 180 degrees out of phase with the phase current of the conductor that the field surrounds. If the shield/sheath resistance were zero, the induced sheath current would be almost equal and opposite to the phase current. Fig.2.5 shows the variation of the magnetic field of a cable circuit as a function of cable shield/sheath resistance [18].

Single-point grounding

This type of shield/sheath grounding method eliminates the induced shield/sheath currents completely, but results in relatively high shield/sheath voltages. It is recommended that a ground continuity conductor is provided with altered position along the cable to minimize the induced current which in turn has minor effect on the total magnetic field in the vicinity of the cable circuit.

(II) Cable installation parameters

The depth of burial of cables in the earth can have a significant effect on the value of the magnetic field above the ground, because of the increased distance from the conductors to the surface. The reduction in magnetic field values is limited to areas that are close to the center line of the cable. Increasing the depth of burial does little to decrease the field values at distances from the cables which are greater than several times the burial depth of the cable circuit as shown in Fig.2.6 [18]. Increasing the depth of burial also has the detrimental effect of reducing the current carrying capacity of the cable circuit as it increases the mutual heating between the cables.

The configuration of the cable phases relative to each other and the spacing between the cable phases have a significant effect on the magnetic field produced by the cables. The closer the three cables in a circuit are placed, the lower is the magnetic field produced by the positive sequence currents. The phase spacing does not significantly affect the magnetic field produced by zero sequence currents. Fig.2.7 [18]

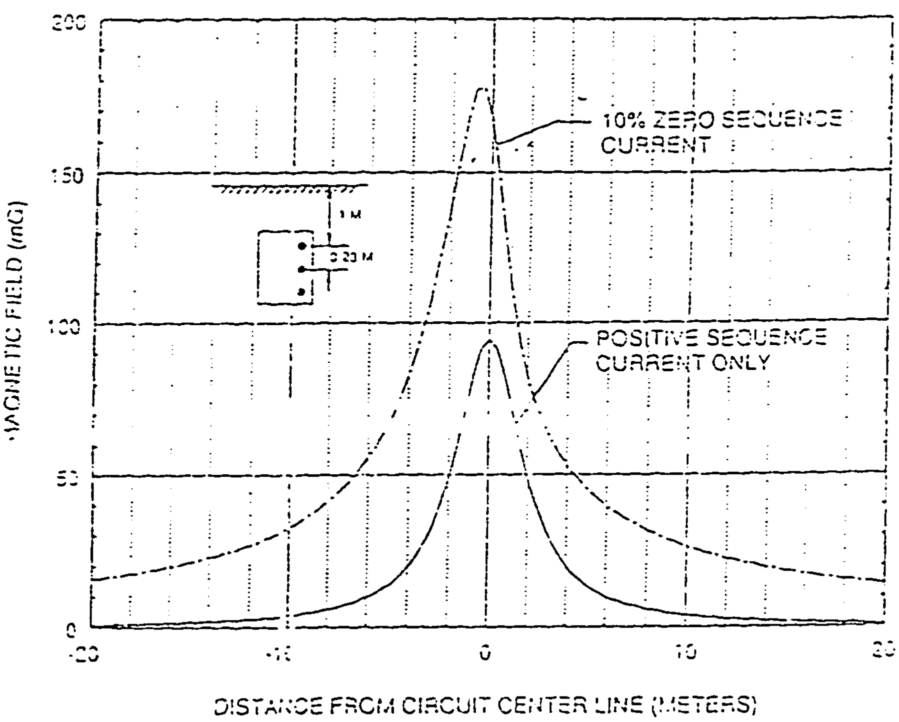


Figure 2.4: Comparison of Magnetic Field Values with 0 and 10%Zero Sequence Current of the Positive Sequence.

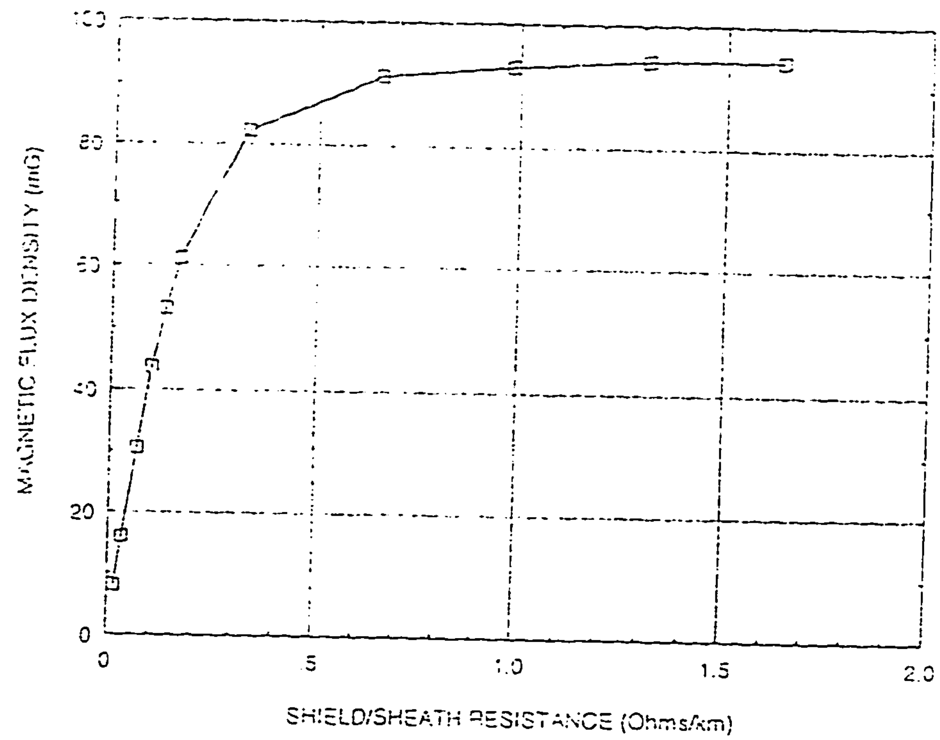


Figure 2.5: Typical Variation of Magnetic Field as a Function of Shield/Sheath Resistance.

shows the effect of both spacing and cable installation configuration on the magnetic field produced by the cables. As shown in the figure, the triangular configuration has the lowest magnetic field, followed by the square configuration, and the vertical one. The horizontal configuration, with all cables equidistant form the surface of the earth, has the highest magnetic field values for a given value of the positive current. Increasing the phase spacing between cables increases the magnetic field values for all commonly used cable configurations. The close triangular configuration though being the most desirable one is limited to areas where open trenching installation methods can be used.

The phase relationship of the cables in double circuit installations can have a significant effect on the magnetic field produced by cables. The reverse phased double cable circuit also has a significantly lower magnetic field than a single cable circuit carrying the same amount of power, and the currents in the two parallel is the same. Unequal current values in the two cable circuit with reverse phasing produces higher magnetic field as compared to balanced currents.

2.3 Magnetic Field Calculations

If the magnitude and phase angles of the currents in the cable system are known a simple application of Ampere's circuital law will give the value of the magnetic field in the vicinity of a single-conductor transmission cables. The usual procedure is to assume some positive sequence currents is flowing in the cable circuit that is being analyzed and then calculate any current that may be induced in the cable/sheaths for multi-point grounded cable system. Once the induced currents have been calculated the magnetic field value may be calculated by summing up the components of the

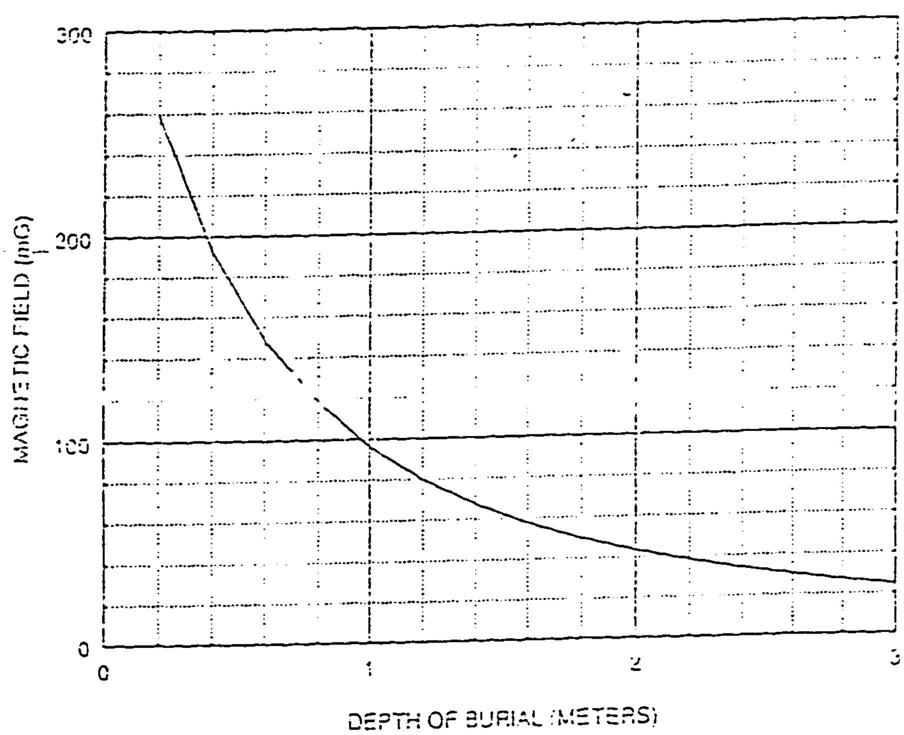


Figure 2.6: Typical Variation of Magnetic Field Directly Above the Cable Center as a Function of Depth.

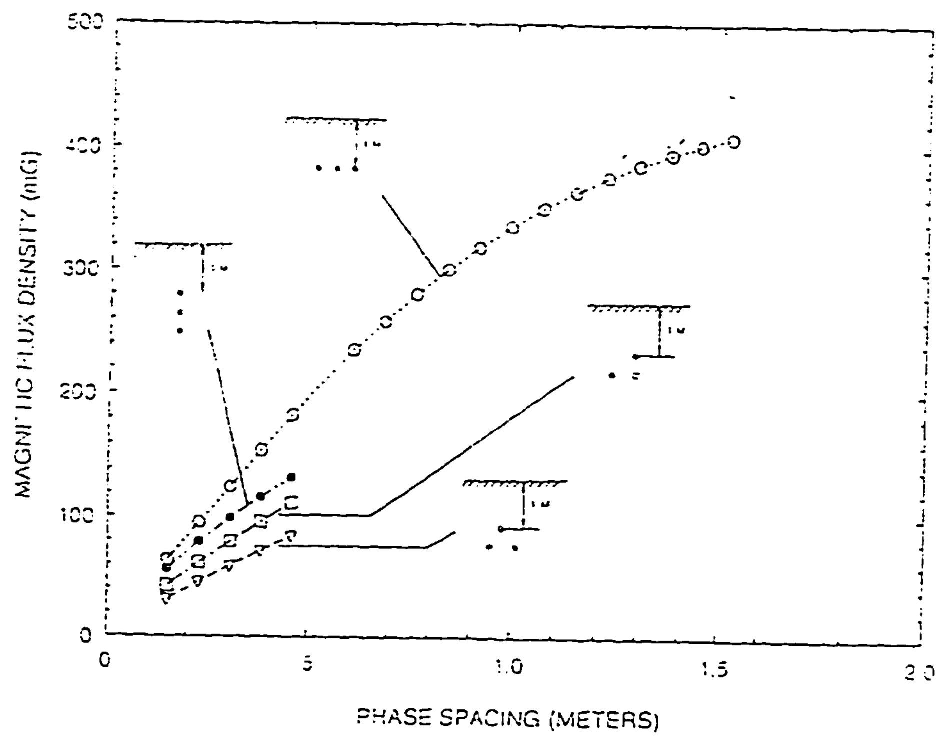


Figure 2.7: Typical Variation of Magnetic Field as a Function of Phase Spacing

total magnetic field that are produced by each of the currents flowing in the cable system [19, 20, 21].

Fig.2.8 demonstrates three cable conductors buried at a depth of d below ground level and placed, from center to center, at a distance of s from each other. To determine the magnetic flux density B at point $P(X_c, Y_c)$, due to currents flowing in these cables, the following assumptions are made:

- The earth has no effect on the magnetic field produced by the cable, i.e., the relative permeability of the earth μ_r is 1,
- The total magnetic field at any point is determined by linear superposition of the magnetic fields produced by the currents flowing in each individual conductor,
- The effect of the induced shield/sheath currents on the magnetic field is negligible,
- Each cable is considered to be infinitely long and straight, and
- The current through the conductors flows out of the paper.

Ampere's Circuital Law states that the line integral of the magnetic field intensity H about any closed path is exactly equal to the current enclosed by that path.

$$\oint \bar{H}.\bar{dl} = I \tag{2.5}$$

The Amperes Circuital Law becomes:

$$I = \oint \bar{H}.\bar{dl} = \int_0^{2\pi} H_\phi r d\phi = 2\pi r H_\phi$$

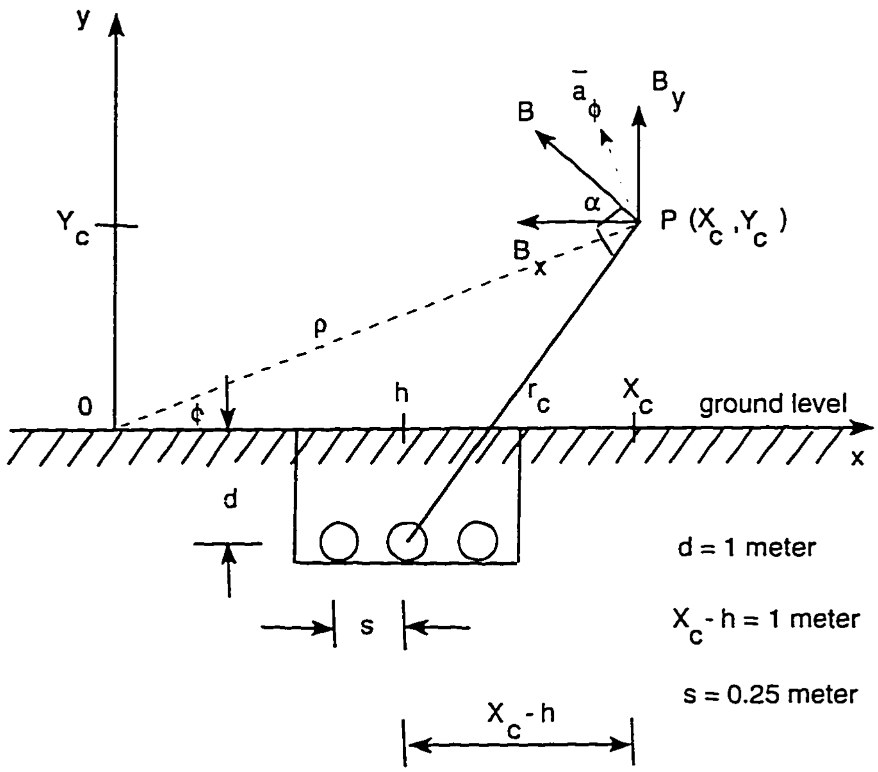


Figure 2.8: Three Buried Underground Cables for Calculation of Magnetic Field.

or

$$\bar{H} = \frac{I}{2\pi r}\bar{a}_{\phi} \tag{2.6}$$

$$\bar{B} = \frac{\mu_0 \mu_r I}{2\pi r}\bar{a}_{\phi} \tag{2.7}$$

where :

$\bar{B}$ is the magnetic flux density in Tesla

$\bar{H}$ is the magnetic field intensity in A/m

μ_0 is the permeability of the free space

$\bar{a}_{\phi}$ is the unit vector along the direction of ϕ

The magnetic flux density can be decomposed into two phasor components (along the direct and the quadrature axes) $\hat{B}_x$ and $\hat{B}_y$:

$$\hat{B}_x = \frac{-\mu_0 \hat{I}}{2\pi r_c^2}(y_c + d) \quad \text{Tesla} \tag{2.8}$$

$$\hat{B}_y = \frac{-\mu_0 \hat{I}}{2\pi r_c^2}(x_c - h) \quad \text{Tesla} \tag{2.9}$$

In each conductor :

$$\hat{I}_1 = I_1 \angle 0^0, \quad \hat{I}_2 = I_2 \angle 120^0, \text{and } \hat{I}_3 = I_3 \angle 240^0$$

Assuming balanced currents $I_1 = I_2 = I_3 = I$, $\hat{B}_{x_{total}}$ and $\hat{B}_{y_{total}}$ can be expressed as,

$$\hat{B}_{x_{total}} = \sum_i \hat{B}_{x_i} \quad \text{and} \quad \hat{B}_{y_{total}} = \sum_i \hat{B}_{y_i} \tag{2.10}$$

The magnetic fields X and Y-components can be decomposed into its real and imaginary parts:

$$\hat{B}_x = B_{x_r} + jB_{x_i} \tag{2.11}$$

and

$$\hat{B}_y = B_{y_r} + jB_{y_i} \tag{2.12}$$

The magnetic flux density vector, at any point in the space ,traces an ellipse as the vector rotates. The maximum magnetic flux density is obtained by the projection of the rotating vectors. The magnitude of the magnetic flux density, in a direction defined by an angle α can be expressed as :

$$B_\alpha^2 = (B_{r_y} \sin\alpha + B_{r_x} \cos\alpha)^2 + (B_{i_y} \sin\alpha + B_{i_x} \cos\alpha)^2 \tag{2.13}$$

For maximum or minimum flux density the derivative of B with respect to α goes to zero. This can be mathematically expressed as :

$$\begin{aligned} \frac{dB_\alpha^2}{d\alpha} &= \tan^2\alpha\, (B_{r_y} B_{r_x} + B_{i_y} B_{i_x}) \\ &+ \tan\alpha\, (-B_{iy}^2 + B_{ix}^2 - B_{ry}^2 + B_{rx}^2) \\ &- (B_{r_y} B_{r_x} + B_{i_y} B_{i_x}) = 0 \end{aligned} \tag{2.14}$$

The appropriate solution to Eqn. (2.16) can be substituted back into Eqn. (2.15), to give the maximum magnitude of the magnetic flux density. This leads to:

$$\hat{B}_x = \frac{-\mu_o \, \mu_r}{2\pi} \left[\frac{(Y_c + d) \, I \angle 120^o}{(X_c - h)^2 + (Y_c + d)^2} + \frac{(Y_c + d) \, I \angle 0^o}{(Y_c + d)^2 + (X_c - h + s)^2} + \frac{(Y_c + d) \, I \angle 240^o}{(Y_c + d)^2 + (X_c - h - s)^2} \right] \tag{2.15}$$

$$\hat{B}_y = \frac{+\mu_o \, \mu_r}{2\pi} \left[\frac{(X_c - h) \, I \angle 120^o}{(Y_c + d)^2 + (X_c - h)^2} + \frac{(X_c - h + s) \, I \angle 0^o}{(Y_c + d)^2 + (X_c - h + s)^2} + \frac{(X_c - h - s) \, I \angle 240^o}{(Y_c + d)^2 + (X_c - h - s)^2} \right] \tag{2.16}$$

Chapter 3

Magnetic Field Management Techniques in Cables

Magnetic field management is basically concerned with the minimization of the effect of magnetic field on the public health front without sacrificing the effectiveness and reliability of the power system.

In response to the public concerns over the health issue, many utilities are being actively involved in electromagnetic field related work. Besides educating the public, many research- type studies are being or have been funded and supported by utilities. In those studies, both magnetic field characterization and magnetic field management in power systems are or were focussed.

In the domain of field characterization, magnetic field in the vicinity of power facilities has been surveyed extensively in the past few years. Major sources generating substantial magnetic field have been identified. These major field sources are under ground cables, overhead transmission and distribution lines, underground structures, sub-stations and other individual power system equipments. The typical value of the magnetic field was found in the range of a few mG up to a few hundreds of mG in living and working places. These values were generally higher than the magnetic field levels identified in epidemiologic studies [22].

Since magnetic field sources in power systems have been identified, the interest of utilities have now shifted to magnetic field management of these sources. The application of magnetic field exposure reduction techniques to existing facilities and equipment is much more difficult than for new constructions. Existing facilities and equipments in general have severe constraints which limits the choice of suitable magnetic field reductions and offers a new set of engineering challenges.

For each magnetic field source there may be a number of design options that would reduce its exposure without altering the function job for which the system was intended. Consideration of the factors which significantly affects the magnetic field produced by transmission cable systems, gives a general approach to the reduction of the magnetic field produced by single-conductor transmission cables. The drawback is that the current carrying capacity of cable gets reduced in most of the methods. The reason for this may be the increase in mutual heating between the cables or by the increase in losses [18].

A general classification of the different approaches for magnetic field reduction is given below:

3.1 Increased Distance Between the Sources and Point of Interest

This approach is simple and straightforward provided there are no physical constraints , such as, space or land availability in the vicinity of the sources. This approach consists of finding ways to avoid the presence of living beings near location of high magnetic fields. This might consist of modifying the work rule, limiting access to high magnetic field zones and installations of equipment far away from the areas frequently used by people.

3.2 Manipulation of Source Geometry and Current

This approach is, at present, widely accepted by utilities. Techniques pertaining to this approach are compacting source geometry, modifying circuit currents or characteristics of magnetic materials of facilities and equipment. Some of these are given below [18]:

1. In case of double circuit of cables (having two cables per phase) there is a mutual cancellation of magnetic fields. This can be utilized in the magnetic field management. The cables should be placed so that they are point symmetric to avoid the induction of zero sequence currents in the two cable circuits. A vertical duct bank installation is probably the most practical installation method to take advantage of magnetic field reduction through mutual cancellation produced by the phase conductors. If the two cable circuits are installed

in side-by-side horizontal configuration, the amount of reduction in the magnetic field that may be obtained by judicious placement of the cable phases is not as great as the case where the cables are installed side-by-side in a vertical configuration. Some transmission cables are installed with the cable circuits in horizontal configurations stacked on top of each other in a duct bank. This "stacked horizontal" configuration would also permit effective magnetic field cancellation between two circuits.

2. Selecting an installation configuration that results in relatively low magnetic fields and placing the cable phases as close to each other as possible so as to taken advantage of mutual cancellation. From this point of view the best is the closed triangular configuration, where the cables are installed with all three phases touching each other. The horizontal installation configuration should be avoided as it results in the highest magnetic field for a given burial depth. The limitation of this method is that placing the cables close to each other results in increased mutual heating and, therefore, reduces the current carrying capacity of the cable.

3. Use of multi-point grounding and a cable with low shield/sheath resistance. This option results in a significant reduction in ampacity for a given conductor size and as such is used only when the above two options do not reduce the magnetic field to acceptable levels. Multi-point grounding makes the most engineering sense for cables installed in a close triangular configuration since the reduction in ampacity from multi-point grounding is much less than for horizontal or vertical configurations. On the positive side, multi-point grounding has been chosen for some transmission cables, regardless of decreased ampac-

ity, because it results in lower shield/sheath voltages, is a less complex system than cross bonded shields/sheaths, and results in somewhat less maintenance than other grounding methods. The cross section, and therefore resistance of transmission cable shield/sheaths is usually provided by the maximum magnitude and duration of fault current that is expected during the life of the cable system. If multi-point grounding is used to reduce the magnetic field levels, then a shield/sheath resistance lower than that required by fault currents considerations will probably be necessary.

4. Placing any ground continuity conductors also reduces the induced current. If a ground continuity is required, as in the case of single-point grounding and some cross bonded systems, then it should be transposed along the route of the cable. The reduction in magnetic field by optimum placement of the ground conductor is usually small as compared to the other options, and hence is to be avoided for significant magnetic field reductions.

5. Increase of the depth of burial also reduces the magnetic field directly above the cables. This is effective only in reducing the maximum magnitude of the field, which is directly above the cables. However, increase of depth of burial leads to decrease in ampacity and increases the cost of installation.

3.3 Magnetic Field Shielding

Each of the above suggested measures have certain drawbacks and quite often do not reduce the magnetic field to the desired level. In some of the cases this method proves to be the only viable solution and will be studied and applied in the proposed work.

Magnetic field shielding with conducting (including high permeability) materials is a common practice in industry. Quite recently, this technique has received extensive attention in electric power engineering. Shielding methods may include the use of induced currents, modification of magnetic flux patterns using high permeability and/or high- conductivity materials, addition of a second field that tends to reduce the original field, and even a change in technology to eliminate $60Hz$ magnetic fields from specific applications.

The ferromagnetic shielding is a passive shielding technique and is a relatively new approach for reducing magnetic fields produced by transmission cables. However, as there were few shielding theories regarding applications in power systems, current shielding designs or implementations are just a practice of experience [22].

Shielding the source and shielding the work area are two different things. The higher the permeability of the material, the better is the shielding. Gaps in shielding can radically affect the flux within the shield. In practice, there is a trade off between the effectiveness of shielding and type as the radius, thickness and size are increased. Finally, it is very important that the shields be continuous for maximum effectiveness.

The various shielding schemes that exist can be separated into two broad categories: shielding subject and shielding source. There are very distinct differences between these two categories.

Shielding a subject means to implement a shield of some sort in order to reduce the field in some relatively small, well defined volume, due to sources of field outside the volume. Shielding the source involves placing a shield to reduce the magnetic field in the "outside" world due to some localized source.

An example of shielding a subject would be to place a highly permeable material around a subject as shown in Fig.3.1 [14]. In this example, the magnetic flux coming down from the top of the figure must get to the bottom of the figure (in order to close some magnetic circuit, of which this flux is the "current"). It does so by taking the path of least reluctance (highest μ). Rather than going through the high reluctance of the air, it chooses the low reluctance path of the high μ material, and is shunted around the subject.

As a second example of shieldig a subject, a wire loop or coil could be placed around the subject as shown in Fig.3.2 [14]. The unperturbed field, B_0, induces a current to flow in the loop are right (resistance and reactance), the current induced in the loop will produce a field which is in the opposite direction of B_0, and the field at the subject is reduced.

It should be noted that, in both examples, there are regions of space in which the magnetic field is increased due to the shield. The shield would need to be designed in such a way as to have those regions located where they have no effect. For instance, in the case of the wire loop described above, the field very close to the wire would be higher than the original field.

The various shielding methods can further be separated into the following categories: shielding with materials of high permeability and/or high conductivity, and shielding with current carrying wires (passive, and active) [14].

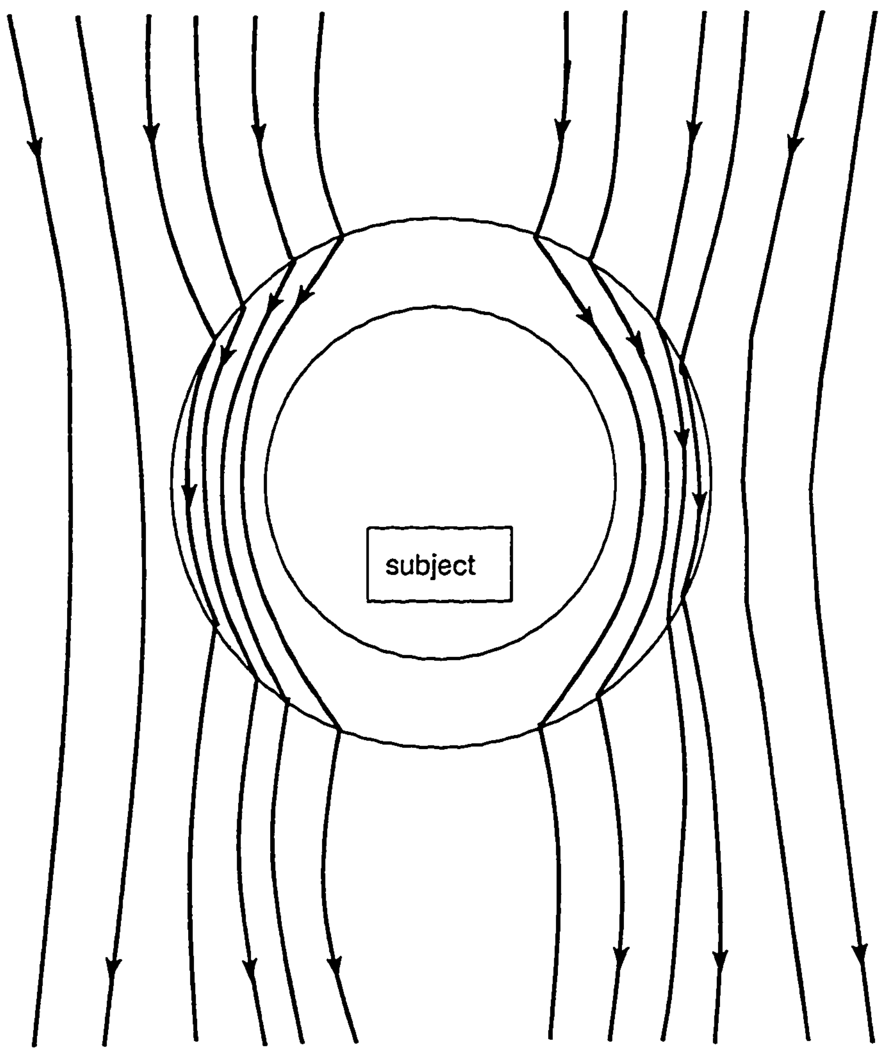


Figure 3.1: Shielding by placing a highly permeable material around a subject.

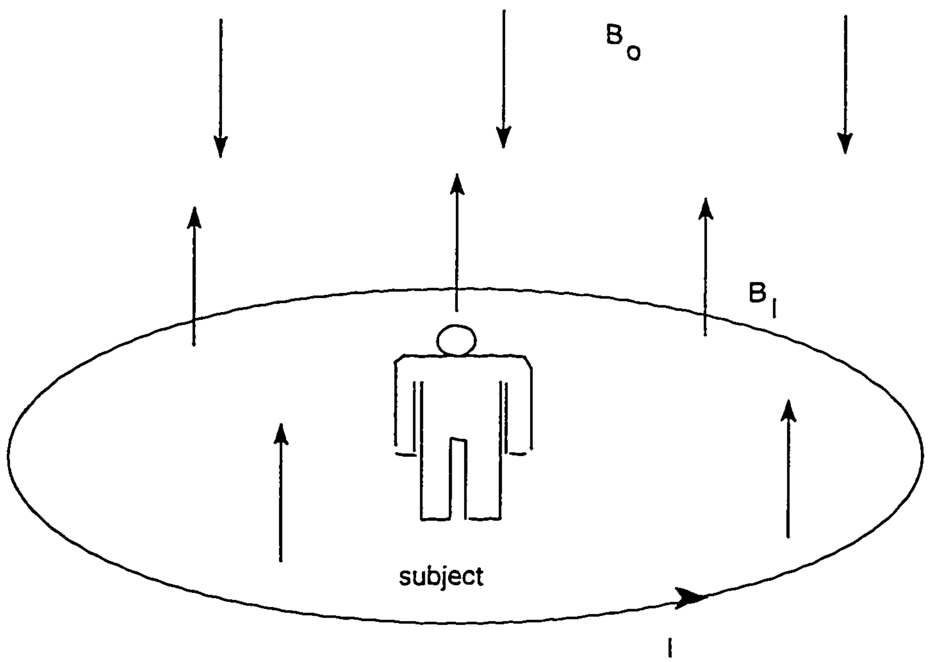


Figure 3.2: Shielding a Subject With a Wire Loop.

3.3.1 Shielding with current carrying wires

Magnetic fields can be shielded (i.e.reduced) by establishing currents in wires such that the fields produced by those currents oppose the fields to be reduced. The shielding effectiveness is, generally, a function of the magnitude and the phase of the current.

Currents in the wires can be established in two ways. They can be induced by the external source of magnetic field, or they can be imposed by electronic devices. If shielding is achieved by induced currents, the shielding is said to be passive, if the shielding is achieved by imposed currents, the shielding is said to be active.

(A) Passive shielding

Magnetic fields can be reduced (shielded) by establishing currents in wires such that the fields produced by those currents oppose the fields to be reduced. Passive shielding (or shielding with "passive" conductors) refers to the use of currents induced in conductors by existing (or ambient) magnetic fields to reduce (shield) these fields in a certain region. From the basics we know that a time varying magnetic field passing through a closed loop, will induce a voltage into the loop (Faraday's law) given by the following equation,

$$e.m.f = -\delta\phi/\delta t \tag{3.1}$$

If the loop is a conductive wire, the voltage will cause a current to flow. This current will set up its own magnetic field. The net magnetic field in the region will be a superposition of the original field and the field due to the induced current. If the field due to the current in the wire opposes the original field, there will be a reduction of the original field. This is the concept of passive shielding with currents in wires.

Because the voltage induced into the loop is proportional to the derivative of the flux through the loop as shown in Eqn.(3.1) the voltage will be 90 degrees out of phase with respect to the flux. If the impedance of the loop was due solely to its self inductance, there would be another 90 degree shift of the current with respect to the voltage, and, therefore, a 180 degree difference between the original field and the induced current. The magnetic field created by the induced current is in phase with the current, therefore, it will be 180 degrees out of phase with the original field, and will result in a reduction of the original field.

However, the impedance of the loop will have a resistive component, and there will be mutual inductances with respect to other passive loops which may be present. Generally, however, the impedance of the wire loop is usually dominated by its self inductance, and the presence of the loop will cause an overall reduction in the magnetic field level.

It should be noted that in some cases it is possible to over-compensate the original field, and actually cause an increase in field level over some regions. In any case there will be regions in which the magnetic field level is increased due to the induced current in the passive loop, such as very close to the wire of the loop. These regions are, however, generally very localized, and their locations can be controlled (put them where field level is not a concern) [14].

(B) Active shielding

Magnetic fields can be reduced (shielded) by establishing currents in wires such that the fields produced by those currents oppose the fields to be reduced. Active Shielding (or shielding with "active" conductors) refers to any scheme to reduce the magnetic field in certain regions of space by the use of conductors with an imposed current whose magnitude, direction, and phase angle create fields in opposition to the ambient fields and thereby reduce the overall magnetic field in a region.

Currents (magnitude and phase) can be imposed in conductors by electronic devices to reduce the magnetic field levels in certain regions. There are several such devices commercially available, and it is suspected that if magnetic fields become more of a concern, more such devices will appear in the market. It is also possible for a knowledgeable engineer to design and build his/her own service.

These devices generally operate in two ways. The first involves placing a magnetic field sensor (transducer) in the region to be shielded. The sensor provides feedback to an electronic device that adjusts the magnitude and phase of a current being fed to a wire loop around the region to be shielded. The electronic device continually adjusts the current as it attempts to null out the field at the sensor. Such devices can be very effective, but can have stability problems during field transients [14].

A second method is to manually adjust the magnitude and phase of the current being fed to the shielding loop until the field is nullified. This is also a very effective means of reducing fields, but has the obvious drawback that the device must be adjusted every time the field changes. However, the active shielding technique is not developed yet, and is still in the laboratory stages.

3.3.2 Quantifying shielding effectiveness

In order to evaluate the effectiveness of various shielding schemes, it is necessary to define terms which quantify the degree of shielding.There are several ways of doing this which are used in literature on this subject. The terms shielding effectiveness and shielding factor (SF) are most often used.The term shielding effectiveness is a generic term without a rigorous mathematical definition.The term shielding factor has a rigorous mathematical definition and is the standard for quantifying shielding effectiveness.

(A) Shielding factor

The shielding factor is defined as a ratio of resultant field after shielding to that before shielding (open air). Mathematically SF can be expressed as [23]:

$$SF = B/B_0 \tag{3.2}$$

where, B is the rms value of the magnetic field with the shield in place, and B_0 the rms value of the unperturbed magnetic field i.e.the magnetic field without the shield.

Obviously, SF is a function of position. The shielding factor always lies between 0 and 1. The smaller SF is,the more significant is the magnetic field reduction. A unitary value of SF means no shielding, and a zero SF means perfect shielding.

Being the ratio of two magnetic field values, SF is a dimensionless quantity. As an example, if the magnetic field strength was 100 mG at some point in space, and the addition of a shield reduced the field level to 25 mG, SF at that point in space would be equal to 0.25.

In some literature, the shielding factor (sometimes called the attenuation factor) is expressed in dB, defined as [24]:

$$SF = 20log(B/B_0)dB \qquad (3.3)$$

Also, in some cases the shielding factor is defined as in Eqn.(3.2), but with B_0 and B being the phasor magnetic field quantities instead of the rms values. In this case SF is itself a phasor quantity. This accounts for the fact the instantaneous value of SF can also vary sinusoidally in time with the 60Hz magnetic field. For practical considerations, however, the rms quantities are more relevant.

(B) Other Shielding Effectiveness Quantities

Another quantity which is sometimes used to quantify shielding effectiveness is the shielding efficiency (SE). The shielding efficiency is defined as:

$$SE = (1 - SF) * 100 \qquad (3.4)$$

Therefore, if the unperturbed field at some point in space was 100 mG, and the addition of a shield lowered the value to 25 mG, SE would equal 75 % at that point.

Another quantity is called the field reduction factor which is simply the reciprocal of the shielding factor. In the above example the reduction factor is 4.

All the shielding effectiveness quantities could be represented as pure numbers, percentages, dB, or as phasors.

Chapter 4

Underground Cable Magnetic Field Simulation and Management

4.1 Simulation of the Recommended Configurations

There are different conductor layout for single phase and three phase cables that are recommended by the EPRI. The EPRI has not recommended the configuration of the phases. One of the position of the three phases a, b and c is going to give a minimum magnetic field. Hence, the first problem which is addressed in this thesis work is to simulate for different designs and come out with the best solution. The simulation for all these different type of configurations are done for magnetic field calculations using the PCFIELD simulation package which is developed by EPRI. There are three type of configuration for a single phase cable, namely, Stack, Triangular, and Flat. For a three phase cable the flat and the triangular configuration are recommended by EPRI. For each of these conductor arrangements six different diameters of cables are simulated.

In any simulation some assumptions are to be made in order to simplify the problem. In this study the following assumptions are made.

- The loads are assumed to be balanced.
- Neutral and ground currents are ignored.
- The earth resistivity is taken as 1000 ohm-m.
- The sheath resistance is taken as 0.001 ohm/ft.
- The field is calculated at a height of 3.28 ft from ground.
- The range of X-Co-ordinate is taken from -50 to 50 ft.
- A derating factor of 50% has been applied for multiconductor lines.

The six cable sizes that are considered along with their current values are tabulated in Table 4.1. Before discussing the results of the simulation it is important to understand the practical usefulness of the study. Fig.4.1 shows two examples, in example (1) two motors of 1000 h.p. and 5000 h.p. are connected to a 13.8 KV bus. As shown in the above mentioned Figure for the 1000 h.p. motor the full load current and the design currents are calculated as 41.8 and 52.25A. So, one has a choice of using one conductor per phase of #6AWG or two conductors per phase of #10AWG or even three conductors per phase of #12AWG wire. For the 5000 h.p.

Table 4.1: Details of the Cable sizes used in the study

Cable Size (AWG or MCM)	Cable Dia. (inch)	Rated Current (A)	Derated Current (A)
#2/0	1.07	175.0	87.50
#4/0	1.20	230.0	115.0
250	1.31	255.0	127.50
500	1.55	380.0	190.0
750	1.78	475.0	237.50
1000	1.89	545.0	272.50

the design current can be calculated as 261.5A. Hence, one has the option to choose either 3 wires per phase of 125A each or 2 wires per phase of 175A each.

Example (2) shows a 1500KVA transformer connected to a 480V bus on the secondary side. The full load current is 1804.3A as shown in Fig.4.1 and the design current 2255.4A. Therefore, one can use either 10 conductors per phase of 300MCM each or conductors per phase of 500MCMeach. As evident from the above two examples in real life one has to deal with multiconductor lines and it is very important to manage the fields for such cases.

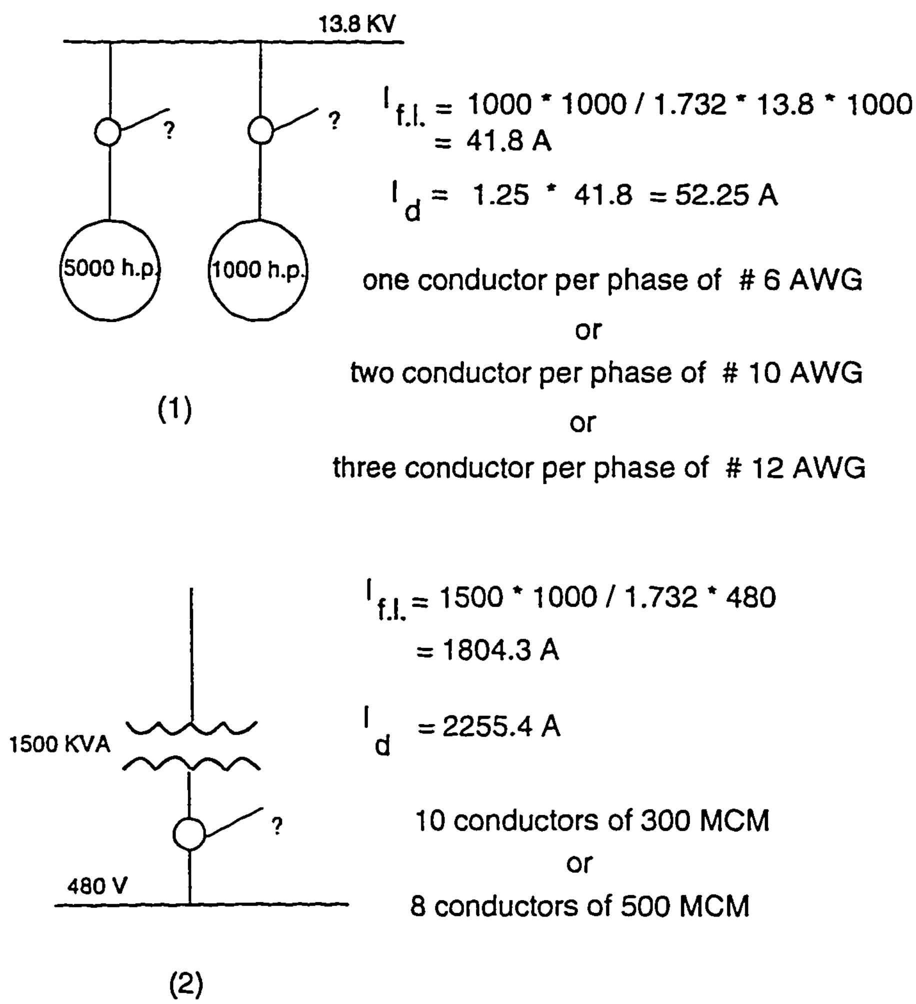


Figure 4.1: Practical Example of a multiconductor line

4.1.1 Simulation for single phase cables

To find the phase configurations so as to have a minimal field different phase locations are simulated. For a two cables per phase there will be 36 different combinations. All these configurations are simulated for a 1.20 inch diameter cable and the results are given in Tables 4.2, 4.3 and 4.4 for stack, triangular and flat arrangement respectively. As evident from Table 4.2 for the stack layout the minimum field is 0.402mG while the maximum is 12.837mG. The minimum occurs when the upper set of conductors are image of the lower set. For the triangular case the minimum field is 2.835 mG (refer Table 4.3) and occurs when the two set of conductors form inverted relationship. For the flat layout the minimum occurs when one set of conductor folds on to the adjacent set (refer Table 4.4) and the value is 1.484 mG.

The conductor configuration obtained for the stack, triangular and flat is shown in Fig.4.2. The phase locations shown in all these figures are corresponding to the minimum field values . In case of a double circuit line (two cables/phase, refer Fig.4.2) the minimum field calculated is for the stack configuration and the maximum is for the triangular configuration. The results of which are tabulated in Table 4.5. As the size of the cable increases the value of the field also increases. The field for flat configuration for a 1.07 inch dia. cable is 0.582 mG which is more than one and a half times of the field due to the stack configuration (0.244 mG). Hence, it is concluded that from the magnetic field point of view for the same load the stack configuration is perhaps the best. The plots for a 1.20 inch dia. cable for the stack, triangular and flat are shown in Figs. 4.3 to 4.9.

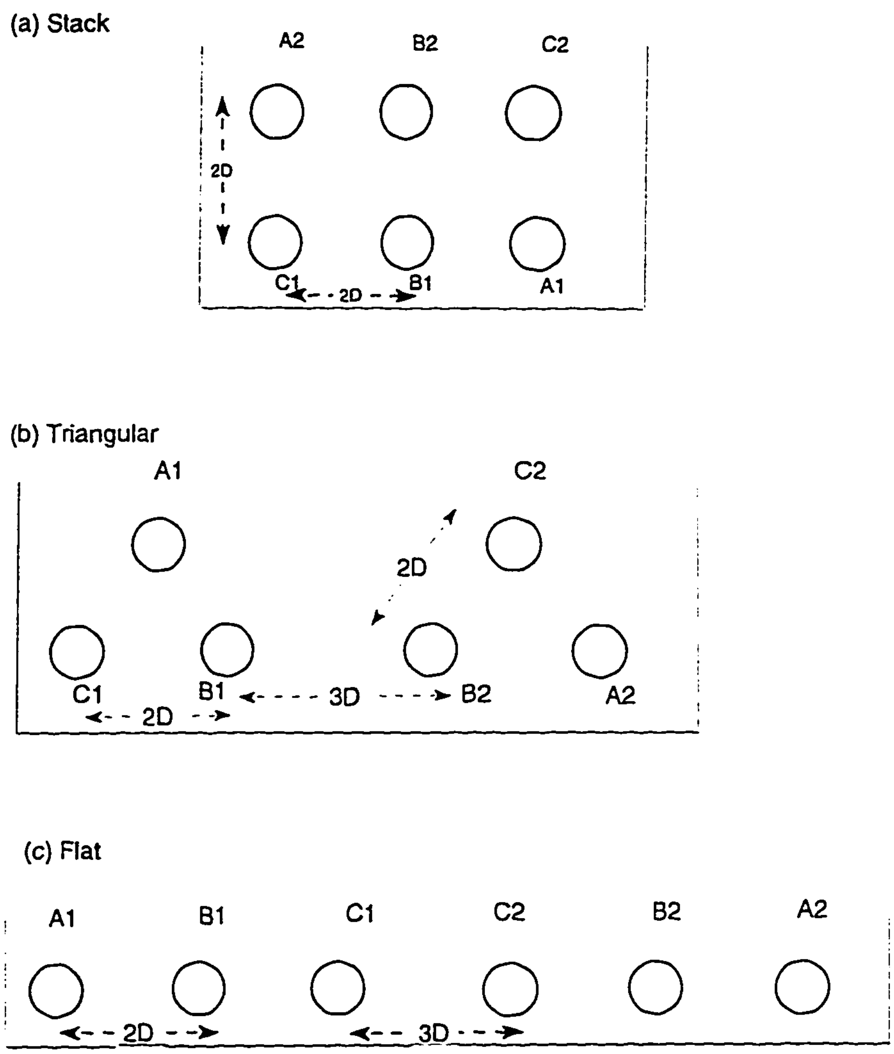


Figure 4.2: A conductor configuration with minimum field of two cables per phase (Single Phase Cable)

Table 4.2: Max. magnetic field values (mG) for all possible phase locations for a Stack Configuration, 2 Cables per phase (Cable dia.= 1.20 inch, Single Phase Cable

a b c a b c (12.837)	a c b a b c (11.12)	c a b a b c (6.428)	c b a a b c (0.402)	b c a a b c (6.428)	b a c a b c (11.12)
a b c a c b (11.12)	a c b a c b (12.837)	c a b a c b (11.12)	c b a a c b (6.428)	b c a a c b (0.402)	b a c a c b (6.428)
a b c c a b (6.428)	a c b c a b (11.12)	c a b c a b (12.837)	c b a c a b (11.12)	b c a c a b (6.428)	b a c c a b (0.402)
a b c c b a (0.402)	a c b c b a (6.428)	c a b c b a (11.12)	c b a c b a (12.837)	b c a c b a (11.12)	b a c c b a (6.428)
a b c b c a (6.428)	a c b b c a (0.402)	c a b b c a (6.428)	c b a b c a (11.12)	b c a b c a (12.837)	b a c b c a (11.12)
a b c b a c (11.12)	a c b b a c (6.428)	c a b b a c (0.402)	c b a b a c (6.428)	b c a b a c (11.12)	b a c b a c (12.837)

Table 4.3: Max. magnetic field values (mG) for all possible phase locations for a Triangular Configuration, 2 Cables per phase (Cable dia.= 1.20 inch, Single Phase Cable)

a a c b c b (6.509)	a a c b b c (6.527)	a c c b b a (2.835)	a c c b a b (6.33)	a b c b a c (3.674)	a b c b c a (6.33)
a a b c c b (6.527)	a a b c b c (6.509)	a c b c b a (6.33)	a c b c a b (3.674)	a b b c a c (6.33)	a b b c c a (2.835)
c a b a c b (6.33)	c a b a b c (3.674)	c c b a b a (6.509)	c c b a a b (6.527)	c b b a a c (2.835)	c b b a c a (6.33)
c a a b c b (6.33)	c a a b b c (2.835)	c c a b b a (6.527)	c c a b a b (6.509)	c b a b a c (6.33)	c b a b c a (3.674)
b a a c c b (2.835)	b a a c b c (6.33)	b c a c b a (3.674)	b c a c a b (6.33)	b b a c a c (6.509)	b b a c c a (6.527)
b a c a c b (3.674)	b a c a b c (6.33)	b c c a b a (6.33)	b c c a a b (2.835)	b b c a a c (6.527)	b b c a c a (6.509)

Table 4.4: Max. magnetic field values (mG) for all possible phase locations for a Flat Configuration, 2 Cables per phase (Cable dia.= 1.20 inch, Single Phase Cable)

abc abc (13.117)	abc acb (11.36)	abc cab (6.524)	abc cba (1.484)	abc bca (6.524)	abc bac (11.36)
acb abc (11.36)	acb acb (13.117)	acb cab (11.36)	acb cba (6.524)	acb bca (1.484)	acb bac (6.524)
cab abc (6.524)	cab acb (11.36)	cab cab (13.117)	cab cba (11.36)	cab bca (6.524)	cab bac (1.484)
cba abc (1.484)	cba acb (6.524)	cba cab (11.36)	cba cba (13.117)	cba bca (11.36)	cba bac (6.524)
bca abc (6.524)	bca acb (1.484)	bca cab (6.524)	bca cba (11.36)	bca bca (13.117)	bca bac (11.36)
bac abc (11.36)	bac acb (6.524)	bac cab (1.484)	bac cba (6.524)	bac bca (11.36)	bac bac (13.117)

Table 4.5: Maximum Value of Magnetic Field obtained for two cables per phase(Single Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration		
		Stack (mG)	Triangular (mG)	Flat (mG)
1.07	87.50	0.244	1.946	0.582
1.20	115.0	0.402	2.835	1.484
1.31	127.5	0.529	3.357	2.002
1.55	190.0	1.092	5.719	4.072
1.78	237.5	1.782	7.937	6.677
1.89	272.5	2.295	9.511	8.623

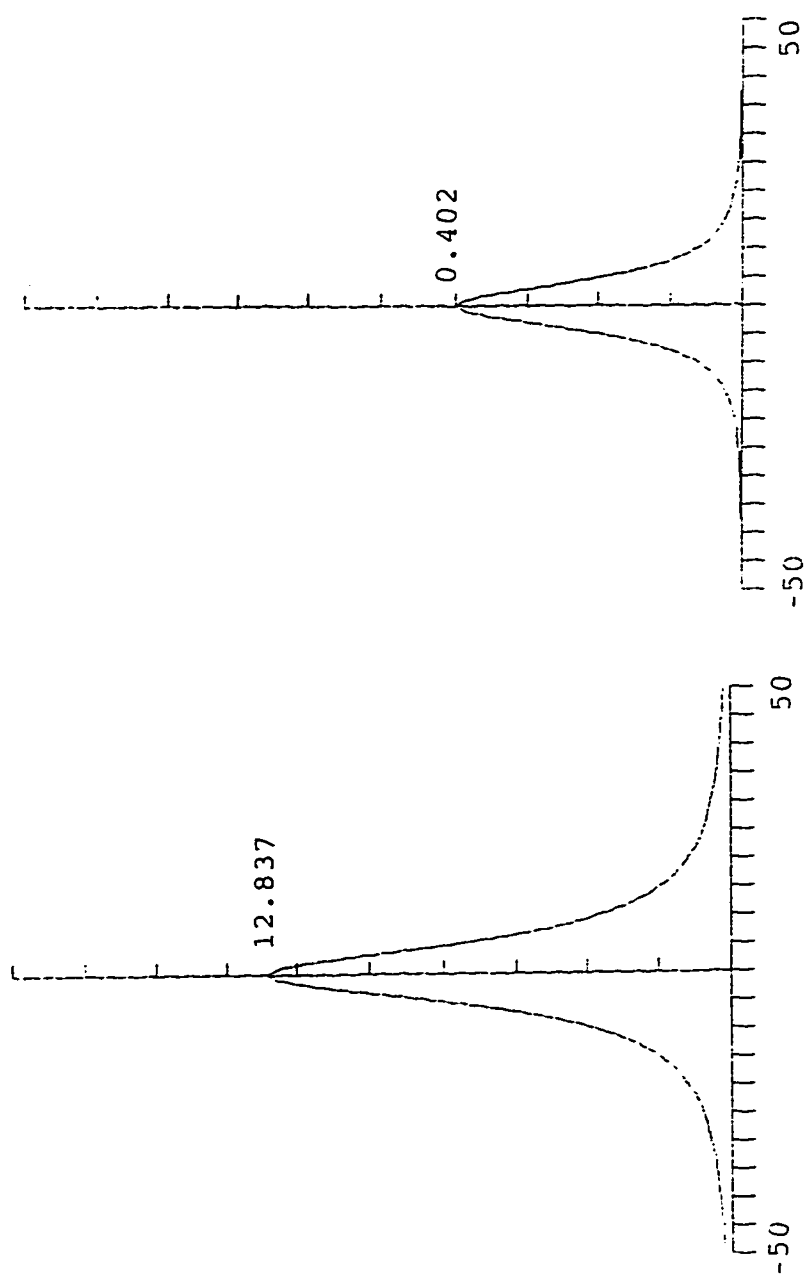


Figure 4.3: Plot for Stack configuration. Two Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

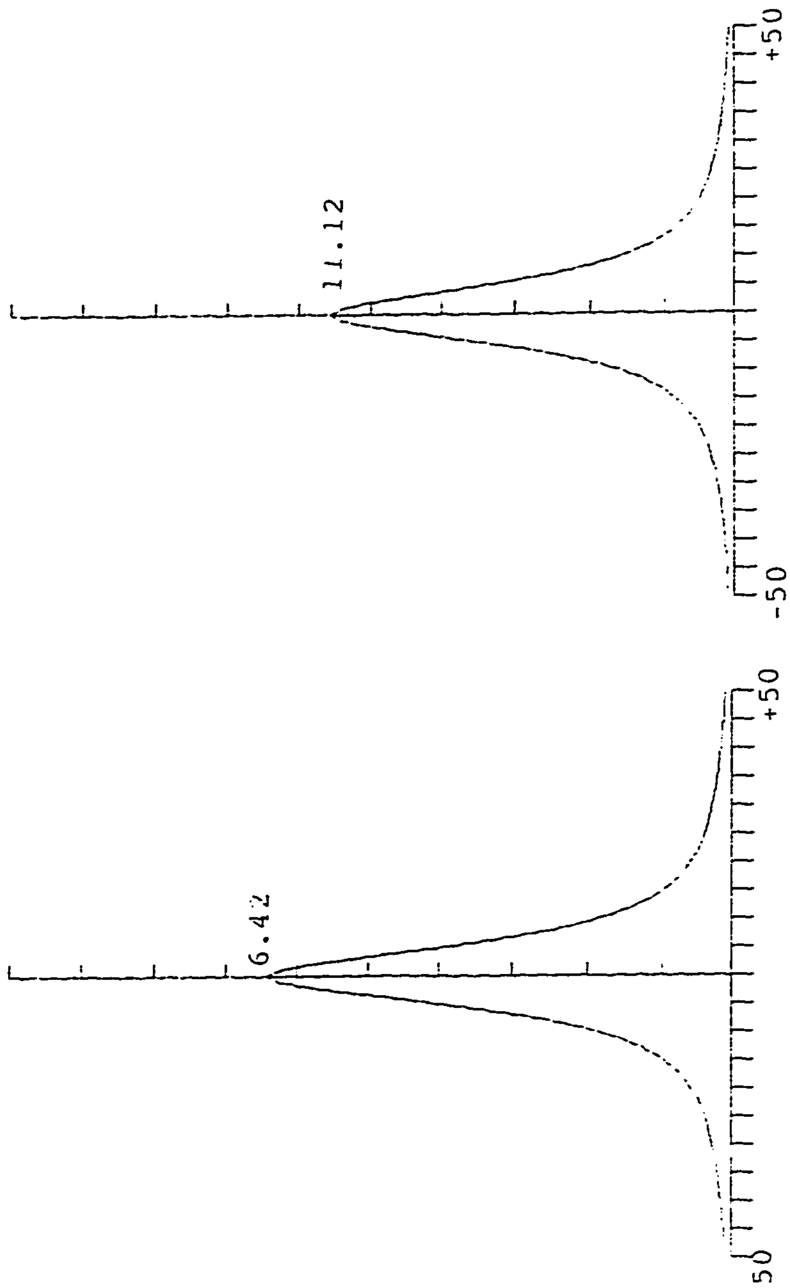


Figure 4.4: Plot for Stack configuration, Two Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

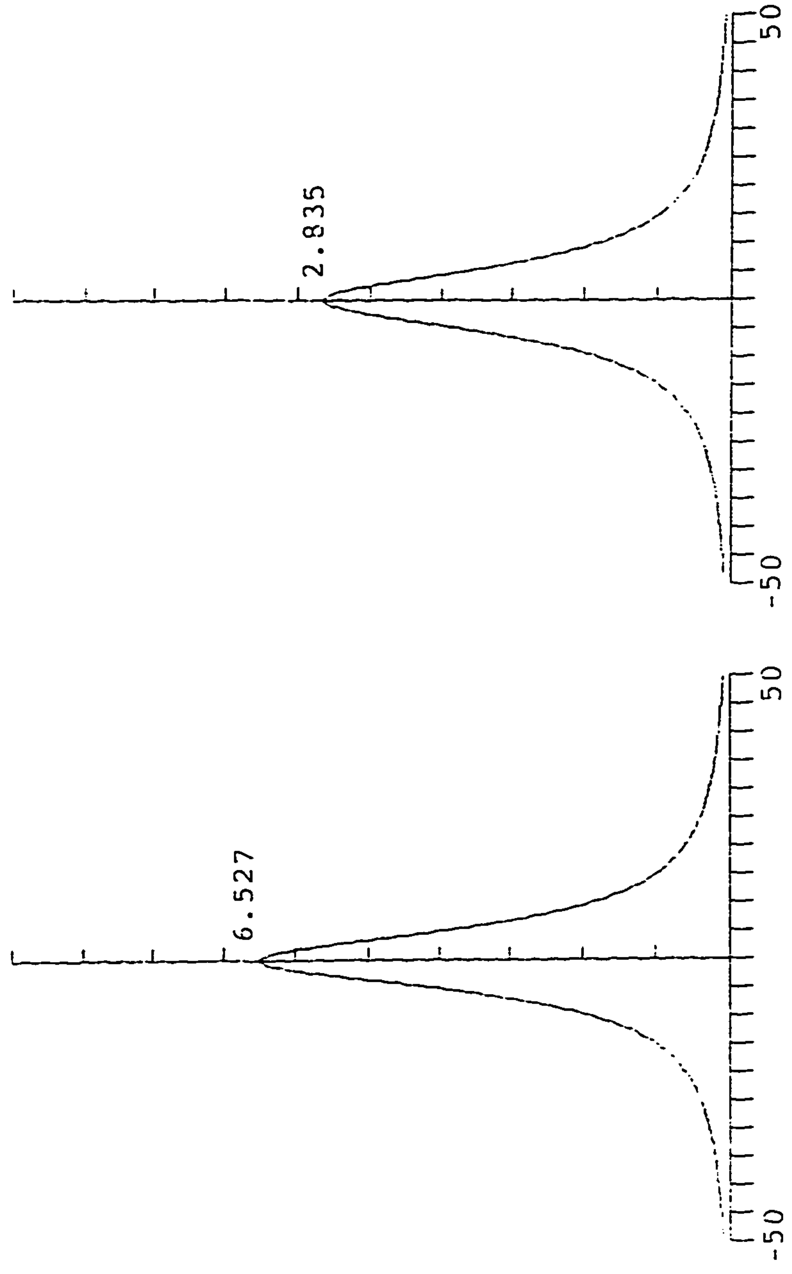


Figure 4.5: Plot for Triangular configuration, Two Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

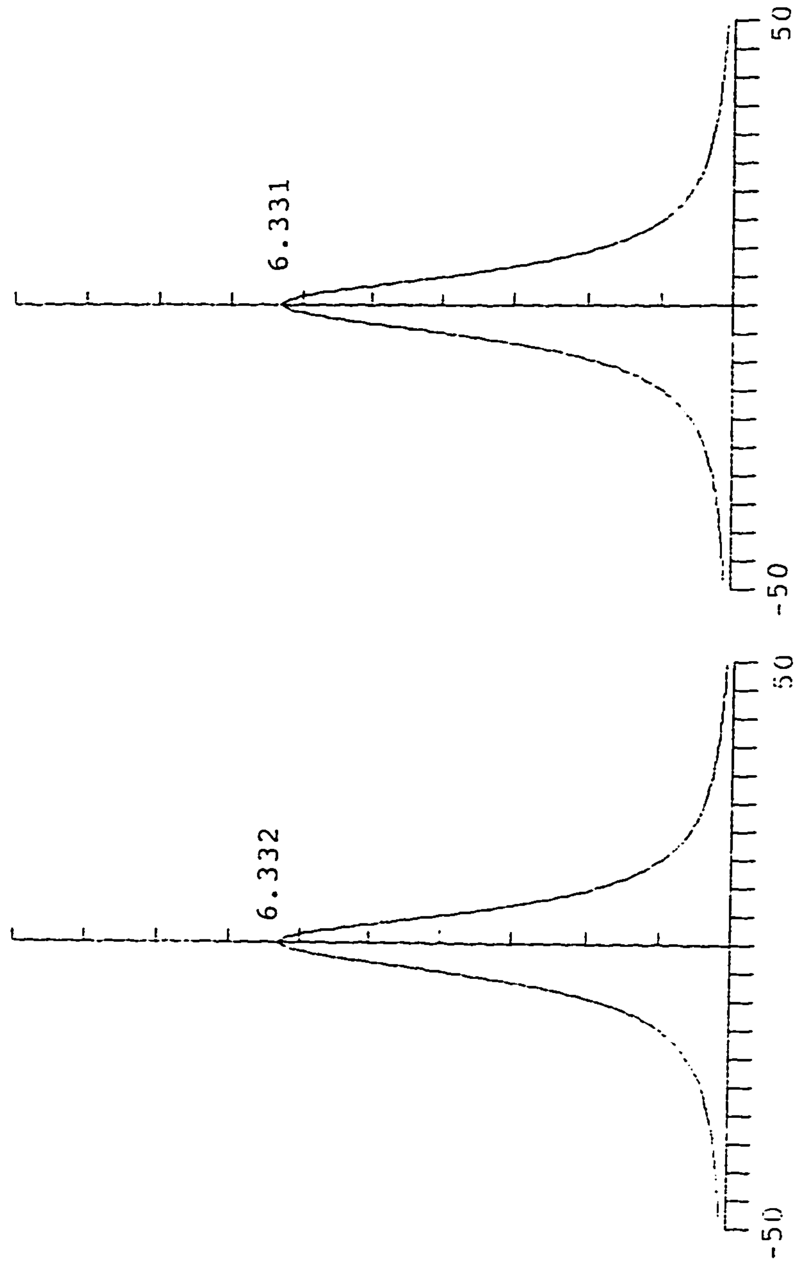


Figure 4.6: Plot for Triangular configuration, Two Cables per Phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

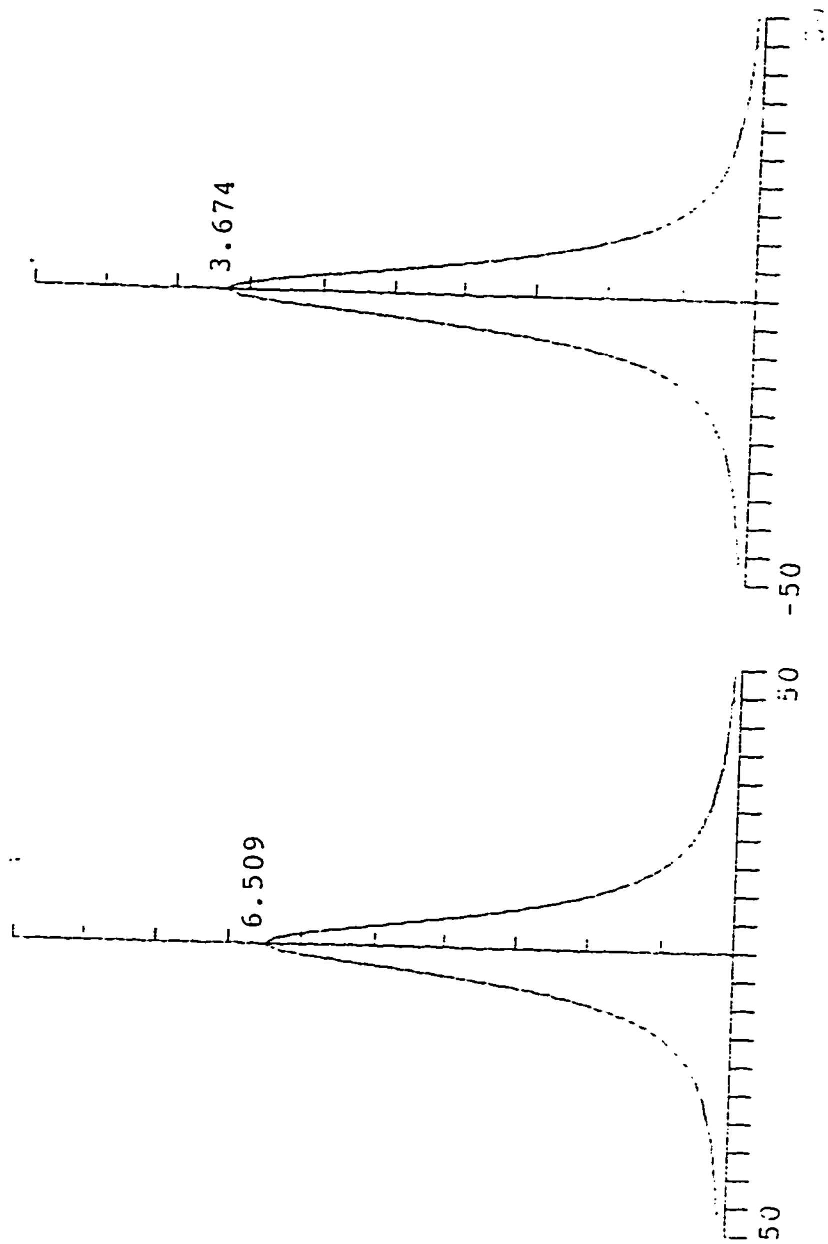


Figure 4.7: Plot for Triangular configuration, Two Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

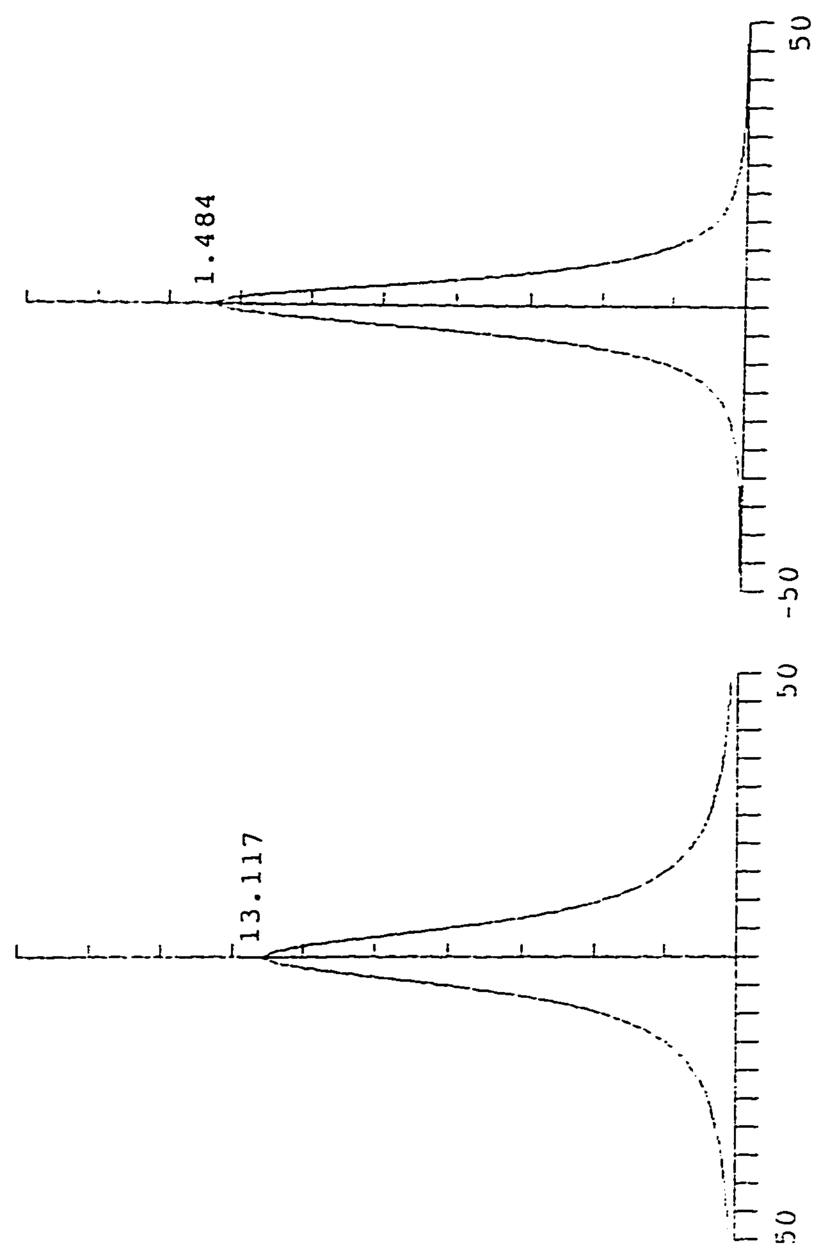


Figure 4.8: Plot for Flat configuration, Two Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

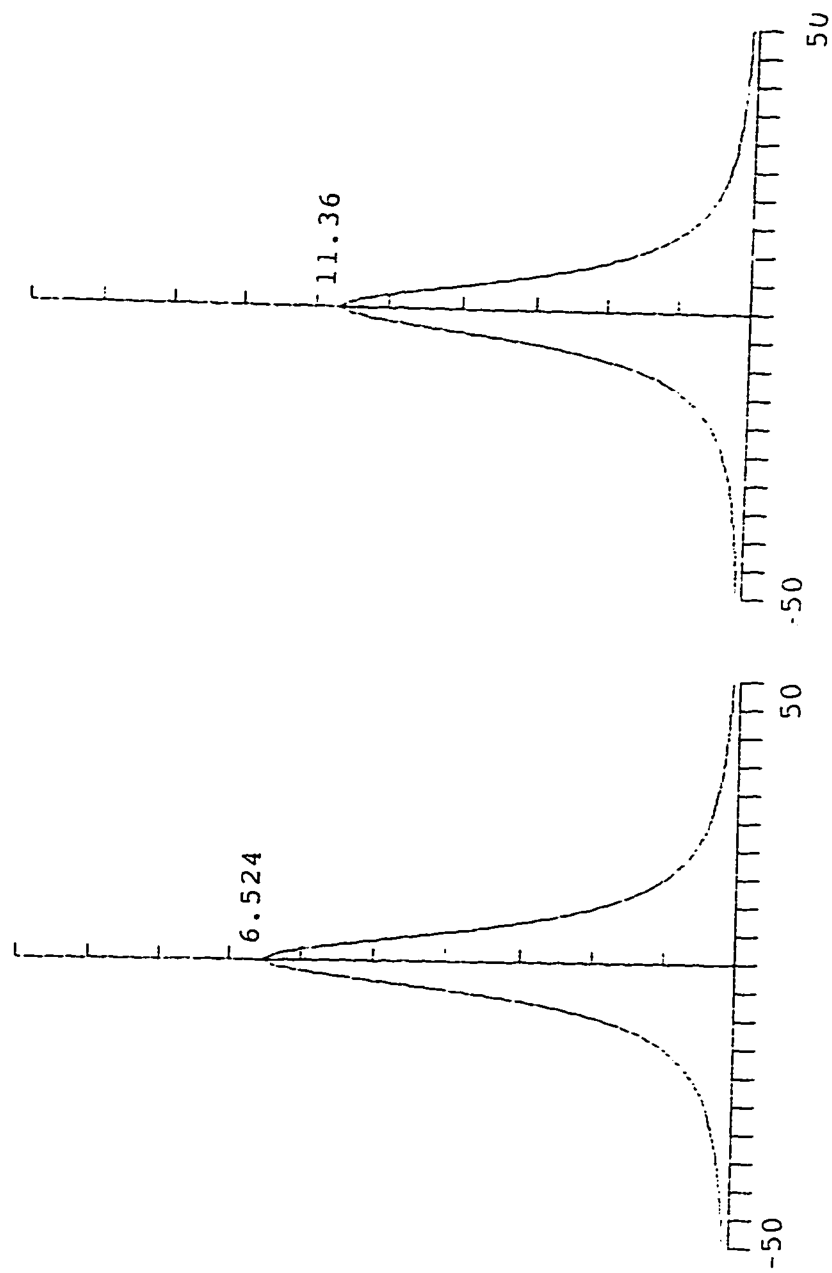


Figure 4.9: Plot for Flat configuration, Two Cables per phase, Cable dia. 1.20 inch (Single Phase Cable). Intermediate cases

In case of three cables/phase the conductor arrangement is as shown in Fig.4.10. The total current carrying capacity is increased as compared to a double circuit by 50%. The results are given in Table 4.6. In this case the worst scenario is for the stack conductor arrangement as less cancellation of the field occurs. The minimum field is obtained for the triangular configuration. For example, for a 1.89 inch cable the resultant field is 24.31, 4.501 and 24.109 mG for the stack, triangular and flat configuration respectively. The stack configuration has fields which are comparable to that of the flat case. The simulation result shows that for three cables per phase triangular configuration is recommended from the magnetic field point of view with the phase positions as shown in Fig.4.10. The plots of the simulated values for a 1.20 inch cable for the stack, triangular and flat are shown in Figures.4.14 to 4.25 and the phase placements corresponding to these plots are as shown in Figs.4.11 to 4.13

In case of four cables per phase (Fig. 4.26) the conductor arrangement for the flat and the stack configuration is identical except for the fact that all the conductors for stack is in one tray, whereas, for flat they are in two trays separated by 18 inches. The magnetic field values are tabulated in Table 4.7.It is observed that the minimum field is for the stack case, the difference between the flat and the stack being in the range of 30 - 35 %. It is also observed that the field for stack is less than the fields for two and three cables per phase due to cancellation from the other phases. The plots of the best and the worst case for all the three arrangements are shown in Figs.4.27 to 4.29. The triangular arrangement is worst for four cables per phase case.

For the five cables per phase the triangular arrangement with the cables per phases configured as shown in Figs. 4.30 and 4.31 gives the minimum field.There are two types of layout for the flat configuration. For cable size of 250 MCM or less the cables are arranged in two trays one having 6 conductors and the other 9, the two trays being separated by 18 inches. The flat generates fields that lies between the stack and the triangular. The results are as per given in Table 4.8. The triangular is the most desirable configuration here. Plots of the best and the worst case are shown in Figs. 4.32 to 4.34.

In the case six cables per phase (Figs. 4.1.1 and 4.36). As given in Table 4.9 up to 250 MCM conductors the field for the stack is minimum and less than the five cables per phase because of the symmetry in the geometry resulting in more field cancellation. For cable size 500 - 1000MCM the flat configuration gives a lesser field and as such is desirable from the magnetic field perspective as compared to the stack. However, the triangular arrangement is most desirable in this case as well. The best and the worst cases are again plotted and shown in Figs. 4.37 to 4.39.

As a conclusion to this subsection we can say that for two and four cables per phase the minimum field for any particular cable size is obtained for the stack configuration. The possible phase location for minimum field is as per shown in the drawings for them. Triangular configuration gives the worst scenario for the two and four cables per phase. In case of three, five and six cables per phase the triangular configuration with the phase locations as shown in the respective drawings gives the optimum result. The stack arrangement gives the highest field for three and five cables per phase. However, for the six cables per phase up to 250 MCM size conductors the flat gives the highest field and above 250 MCM the stack gives the highest field value.

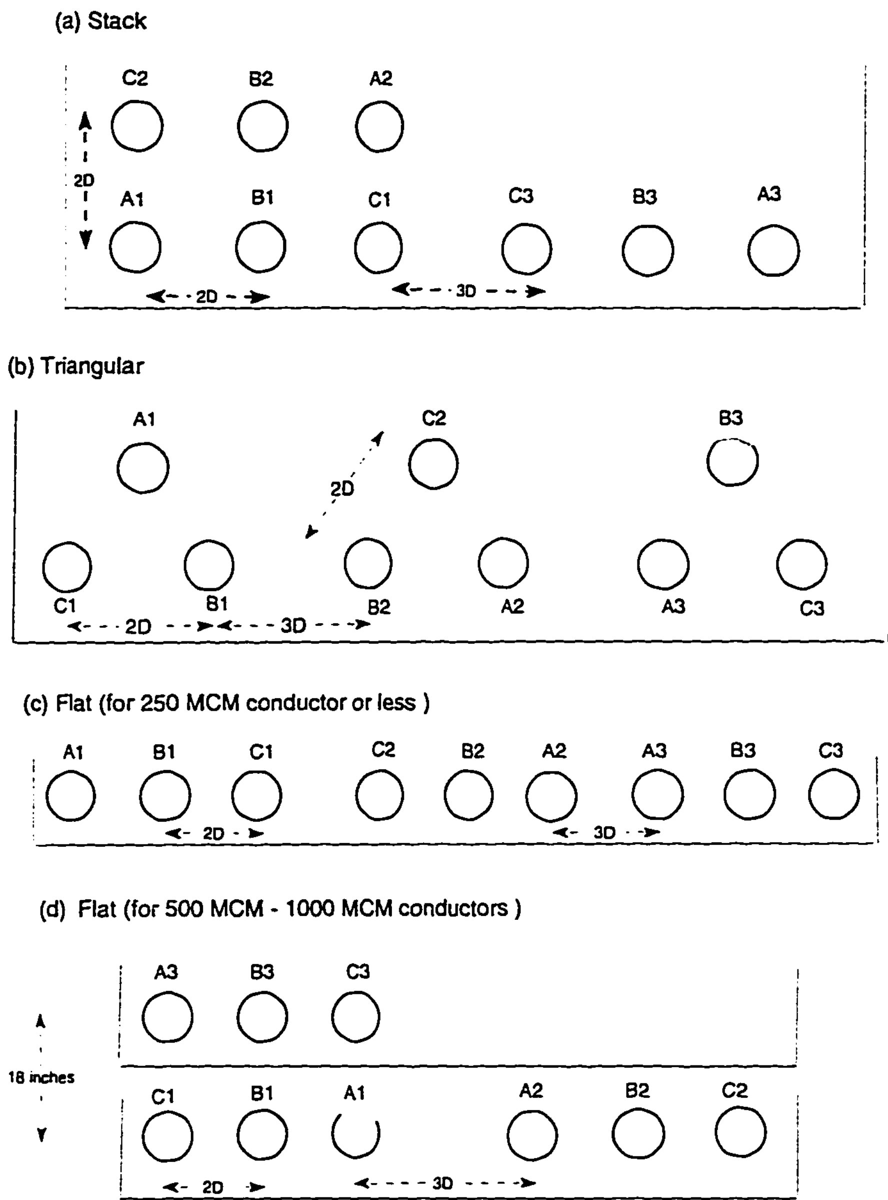


Figure 4.10: A conductor configuration with minimum field of three cables per phase (Single Phase Cable)

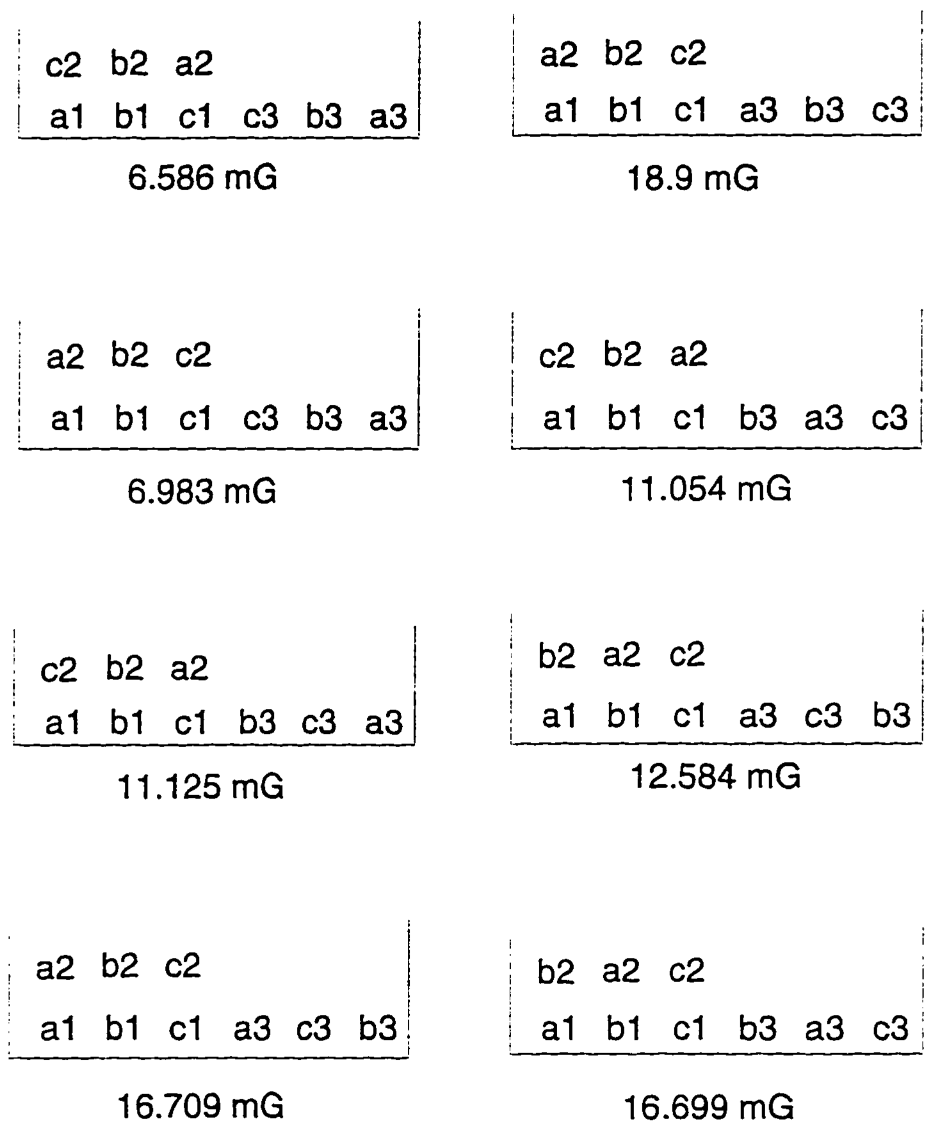


Figure 4.11: Some of the possible configuration of phases for stack layout, three cables per phase (Single Phase Cable)

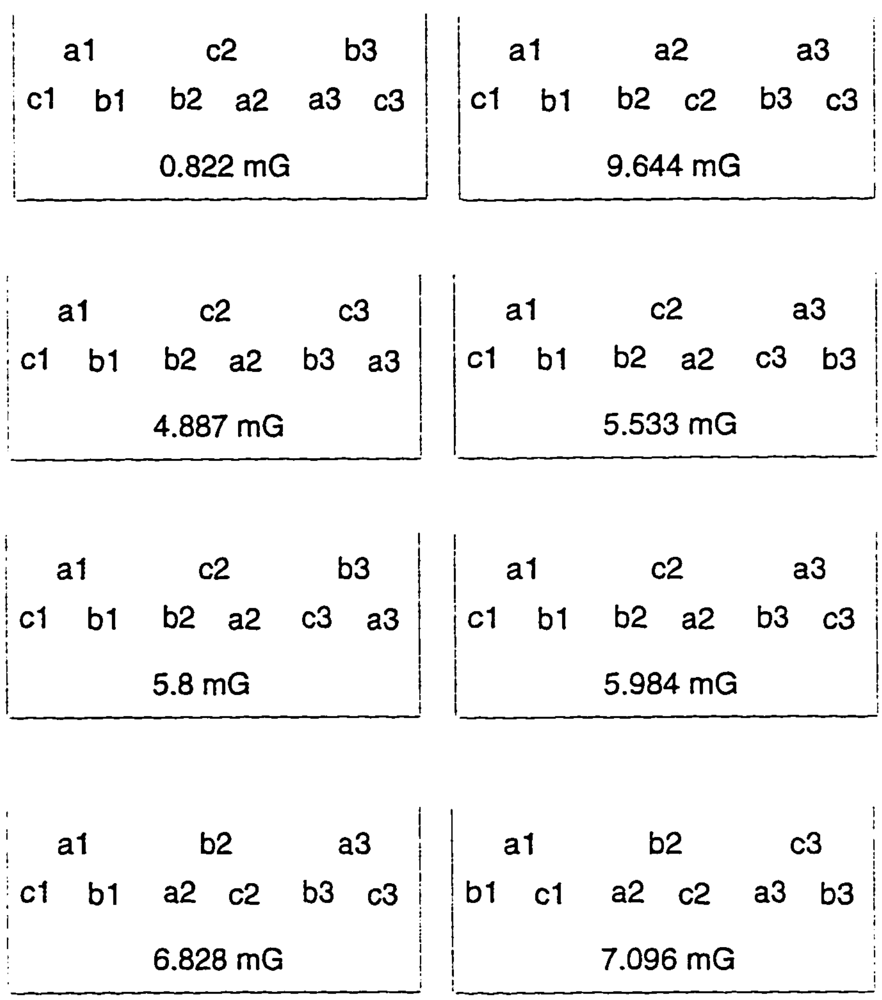


Figure 4.12: Some of the possible configuration of phases for triangular layout, three cables per phase (Single Phase Cable)

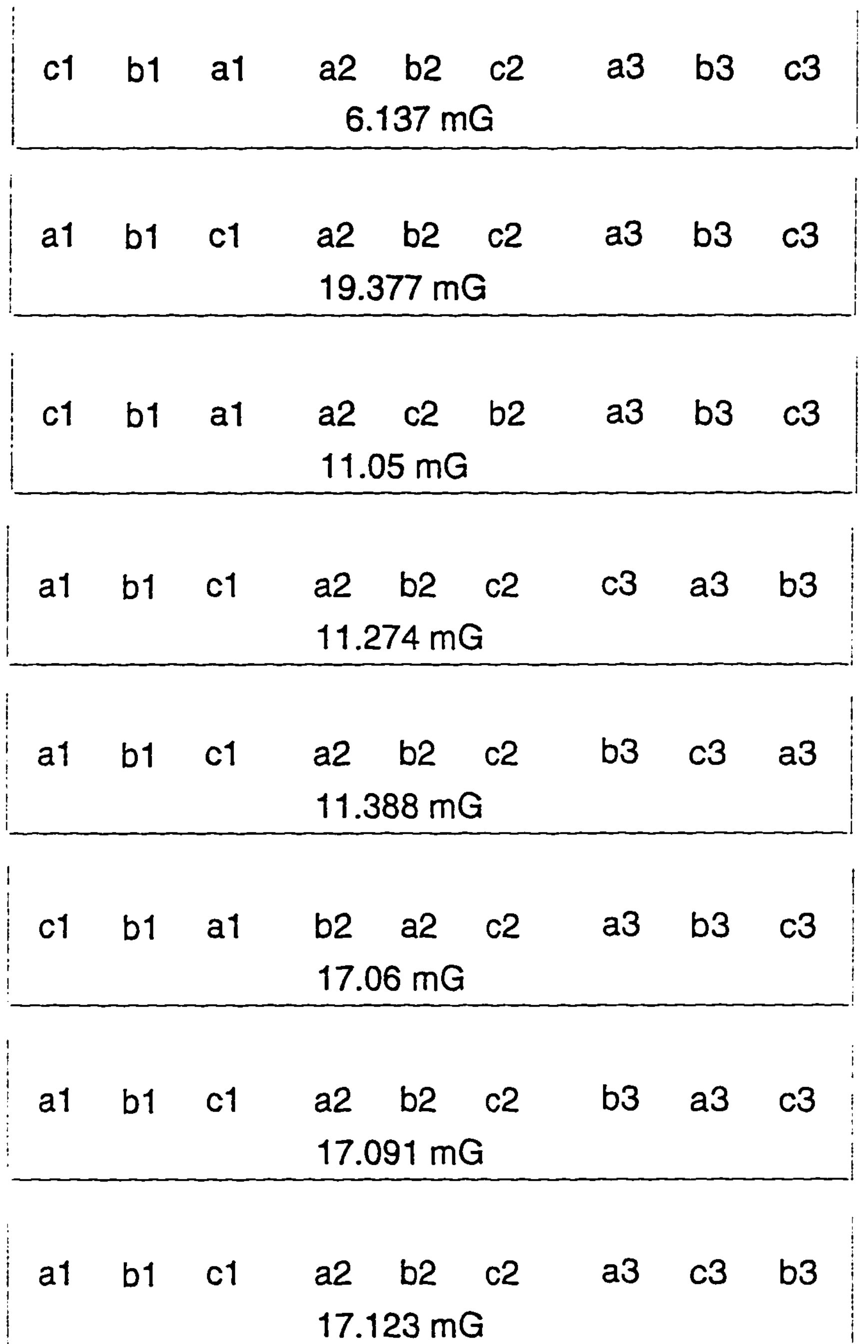


Figure 4.13: Some of the possible configuration of phases for flat layout, three cables per phase (Single Phase Cable)

Table 4.6: Maximum Value of Magnetic Field obtained for three cables per phase(Single Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration Stack (mG)	Triangular (mG)	Flat (mG)
1.07	87.50	4.474	0.502	4.231
1.20	115.0	6.586	0.822	6.137
1.31	127.5	7.961	1.075	7.318
1.55	190.0	13.988	2.193	13.901
1.78	237.5	19.999	3.532	19.847
1.89	272.5	24.31	4.501	24.109

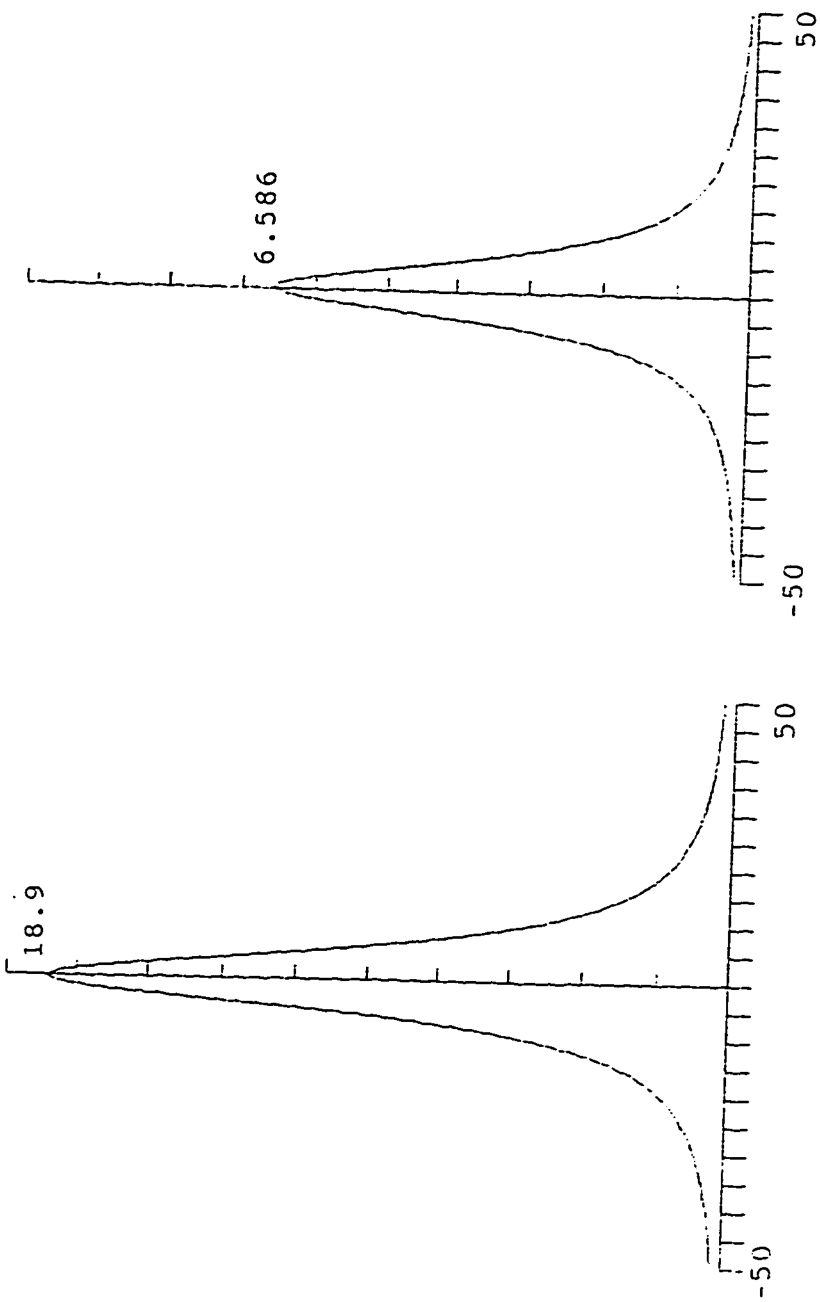


Figure 4.14: Plot for Stack configuration. Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

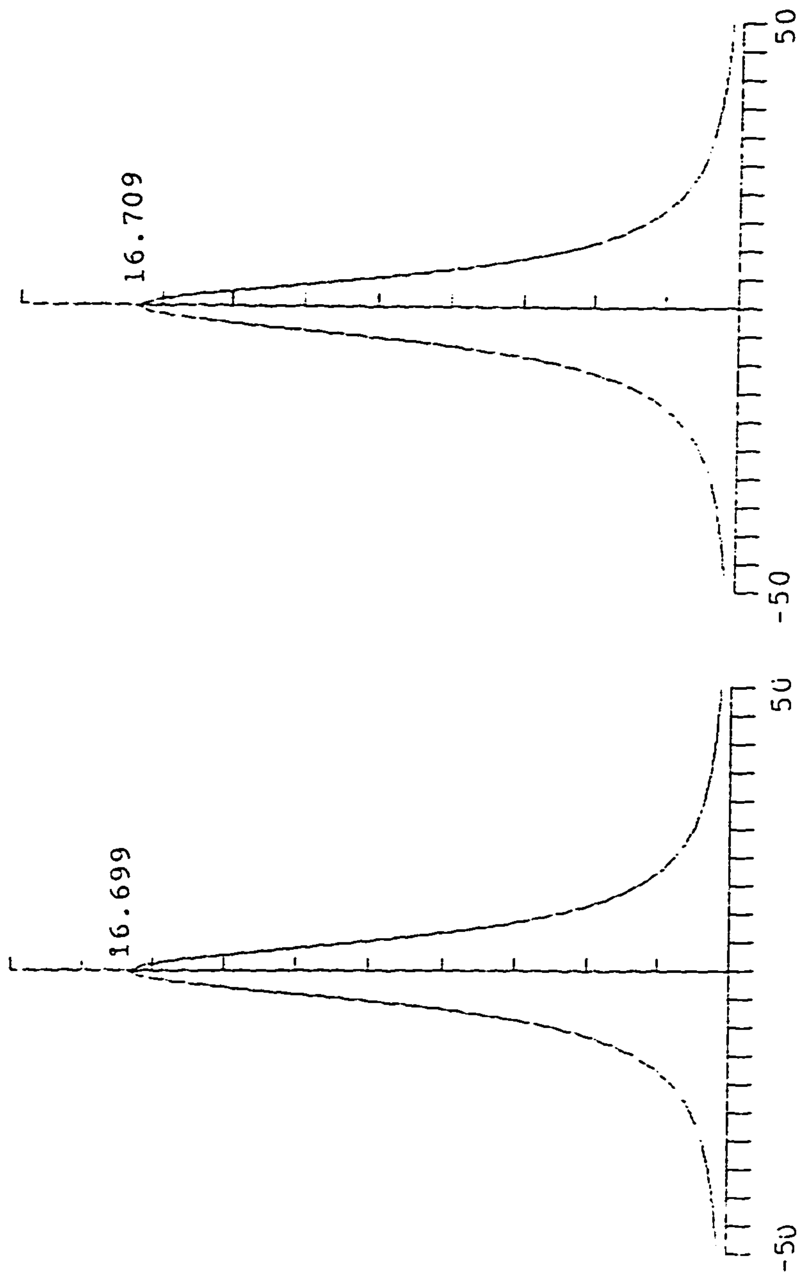


Figure 4.15: Plot for Stack configuration, Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

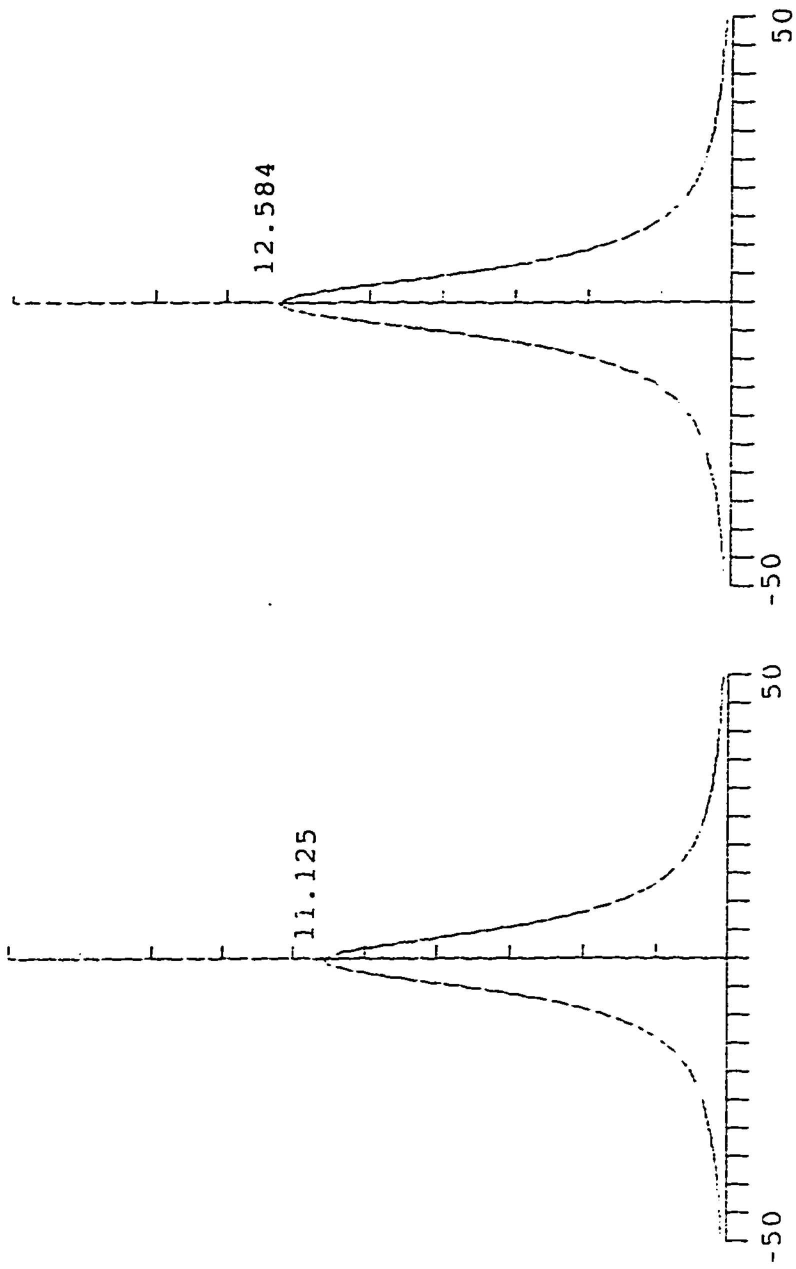


Figure 4.16: Plot for Stack configuration, Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

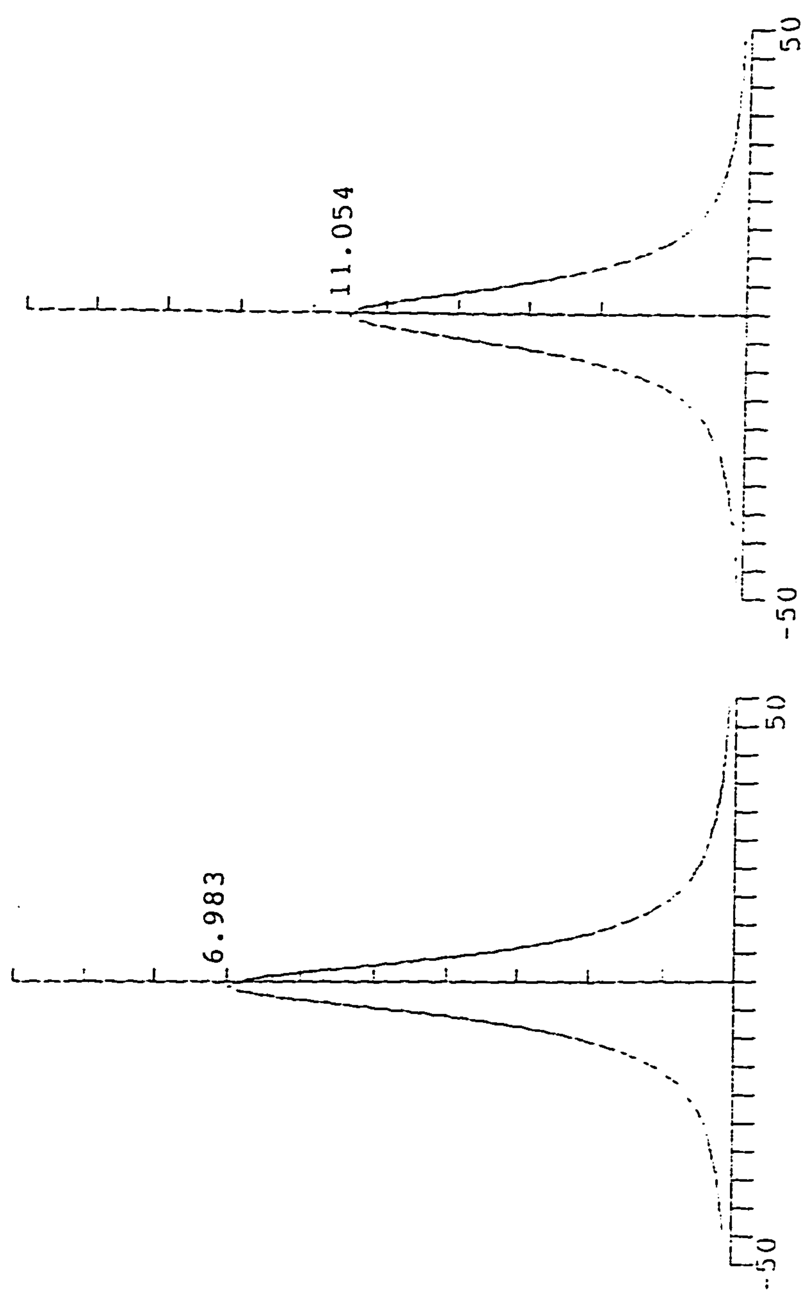


Figure 4.17: Plot for Stack configuration, Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

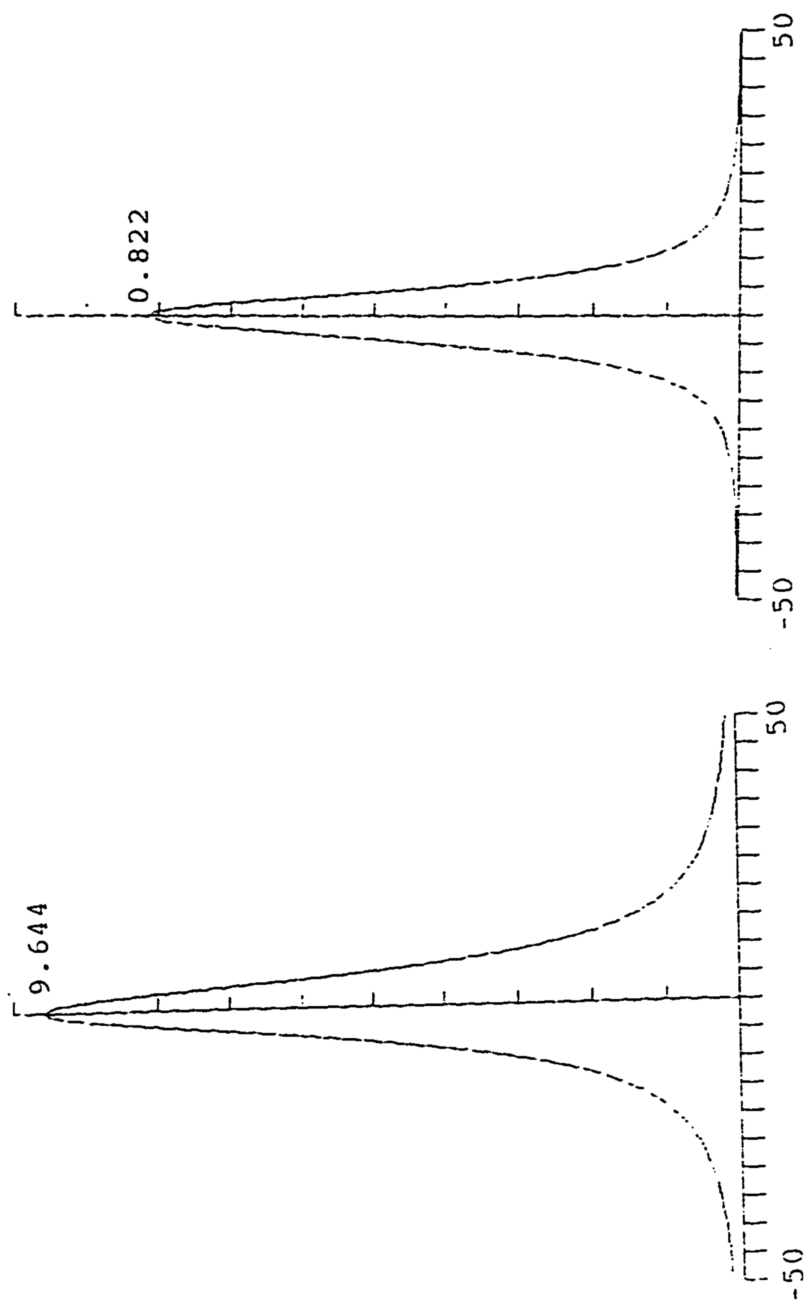


Figure 4.18: Plot for Triangular configuration, Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

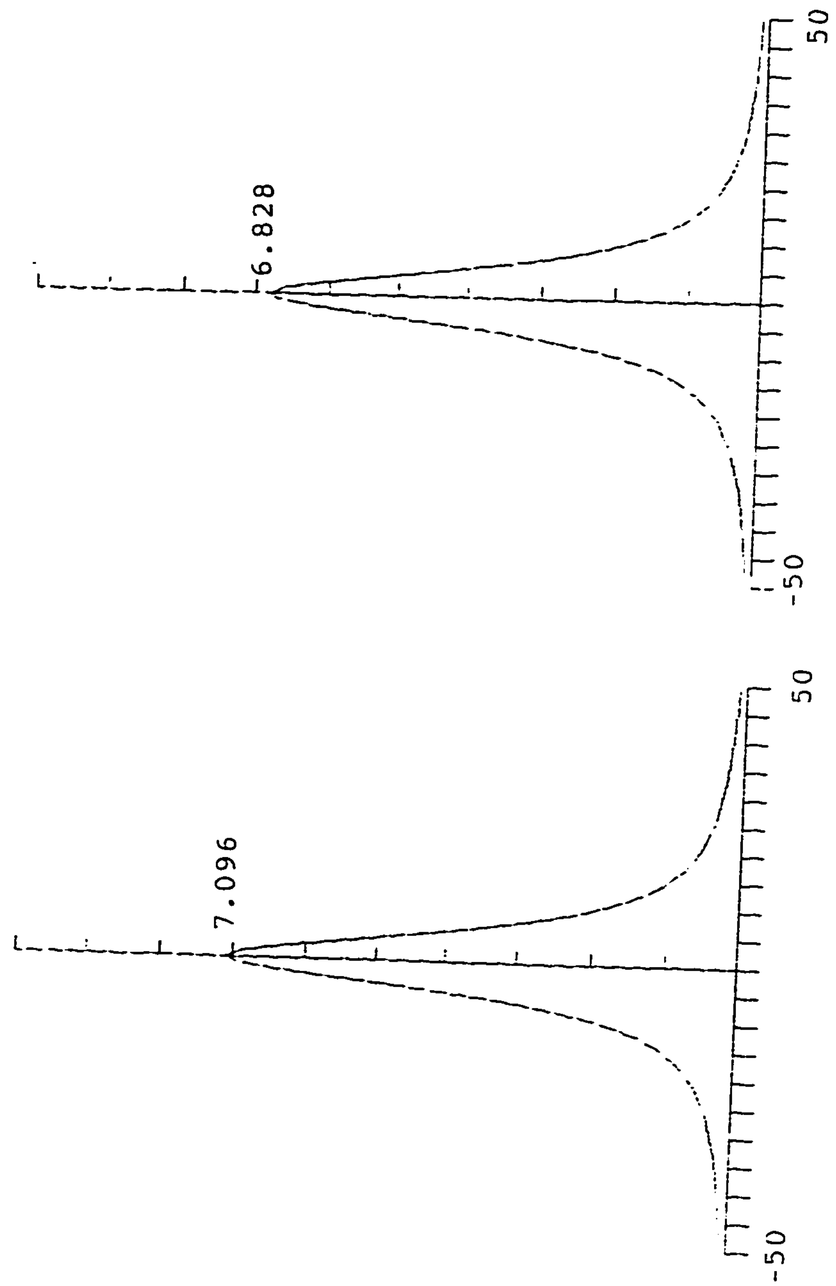


Figure 4.19: Plot for Triangular configuration, Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

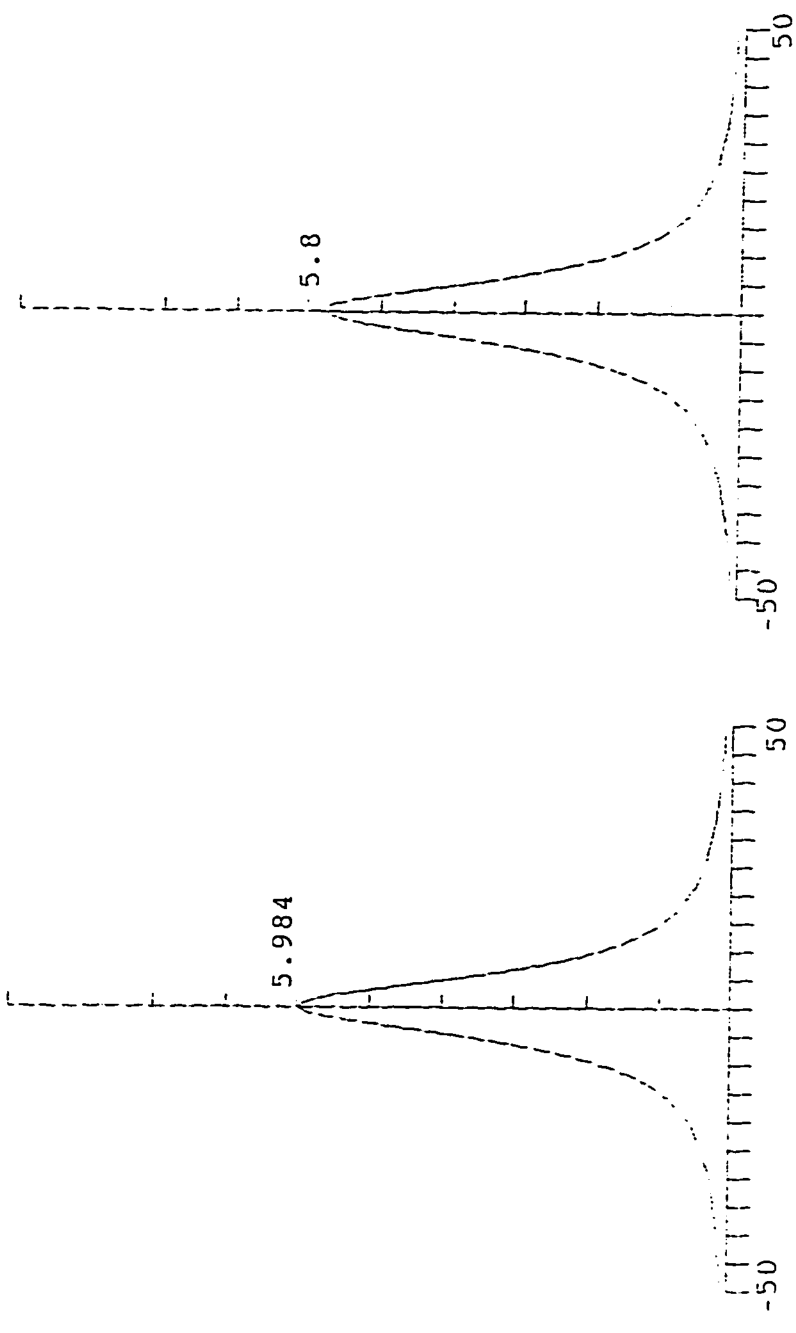


Figure 4.20: Plot for Triangular configuration, Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

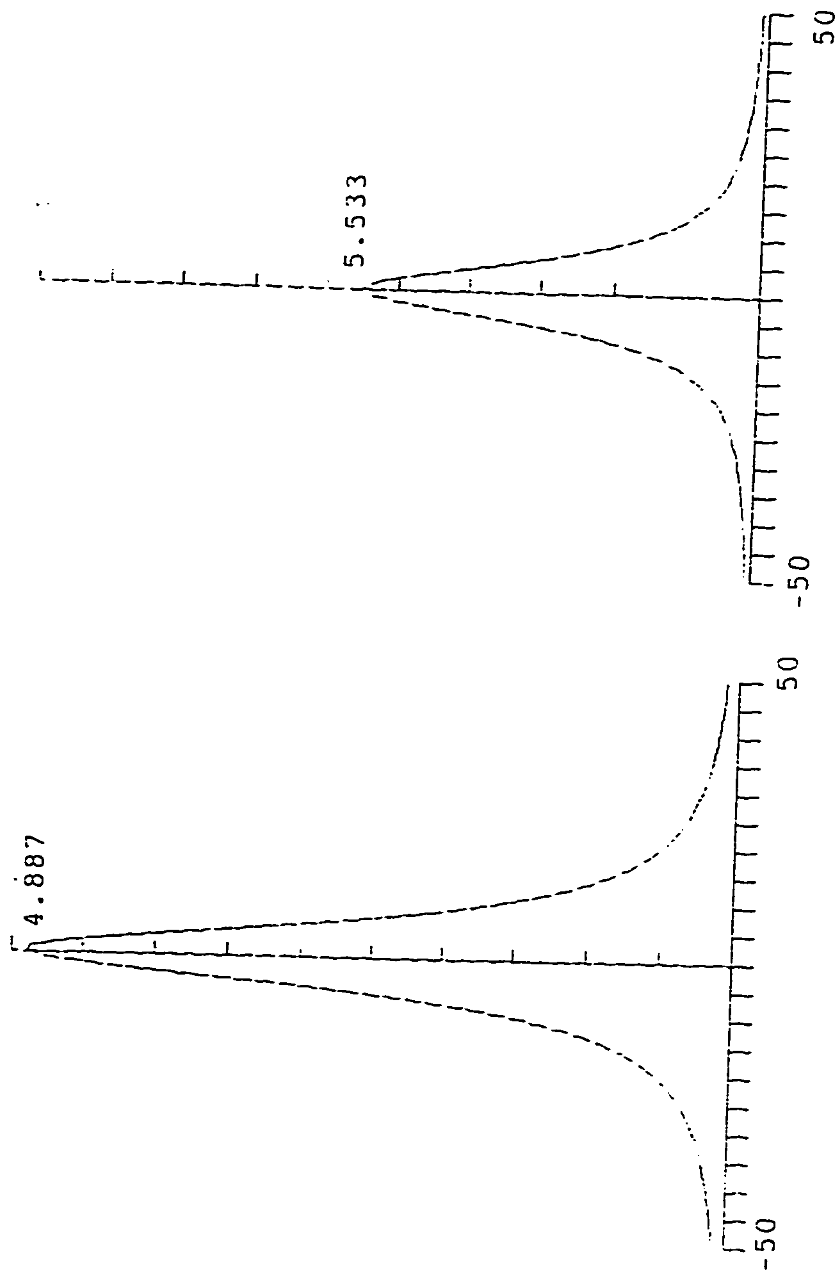


Figure 4.21: Plot for Triangular configuration, Three Cables per phase. Cable dia. 1.20 inch (Single Phase Cable). Intermediate cases

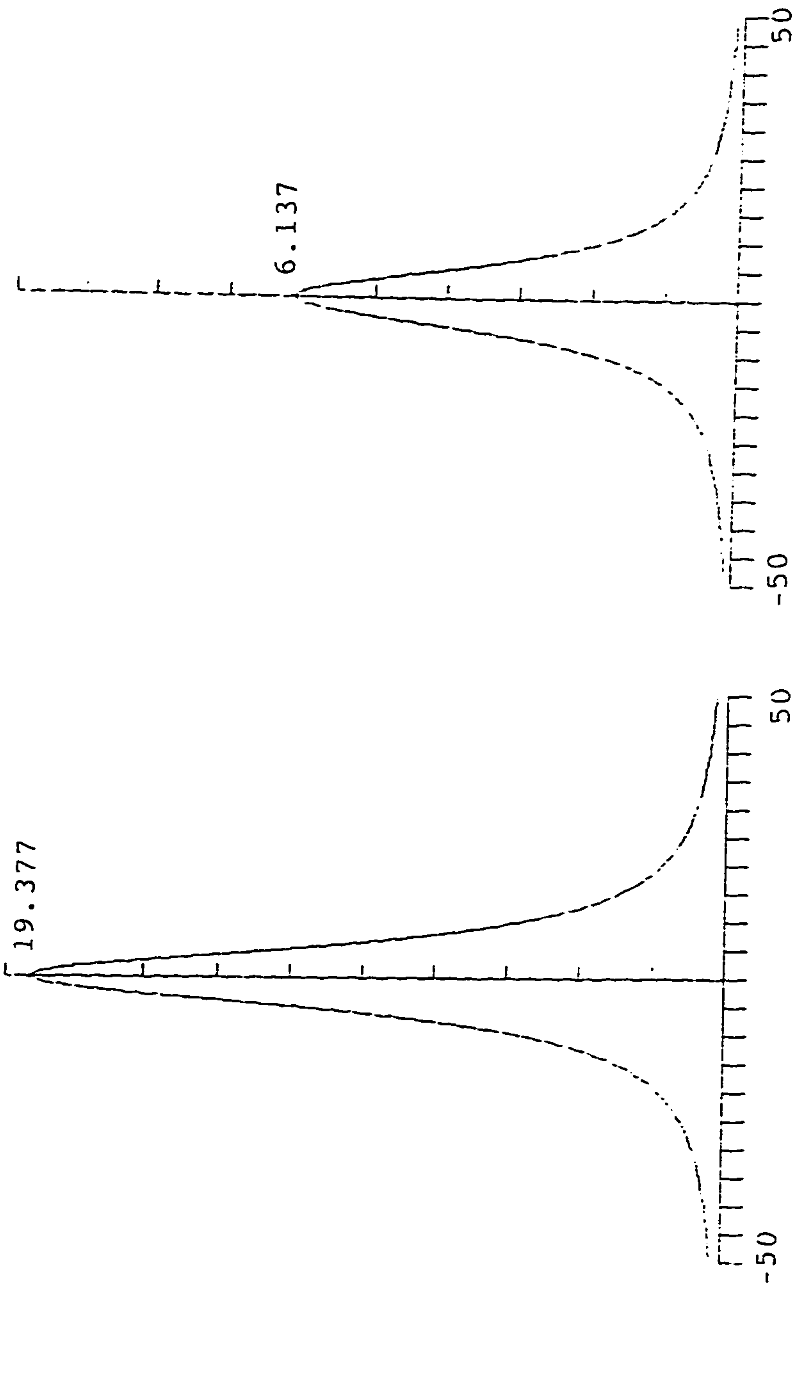


Figure 4.22: Plot for Flat configuration. Three Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

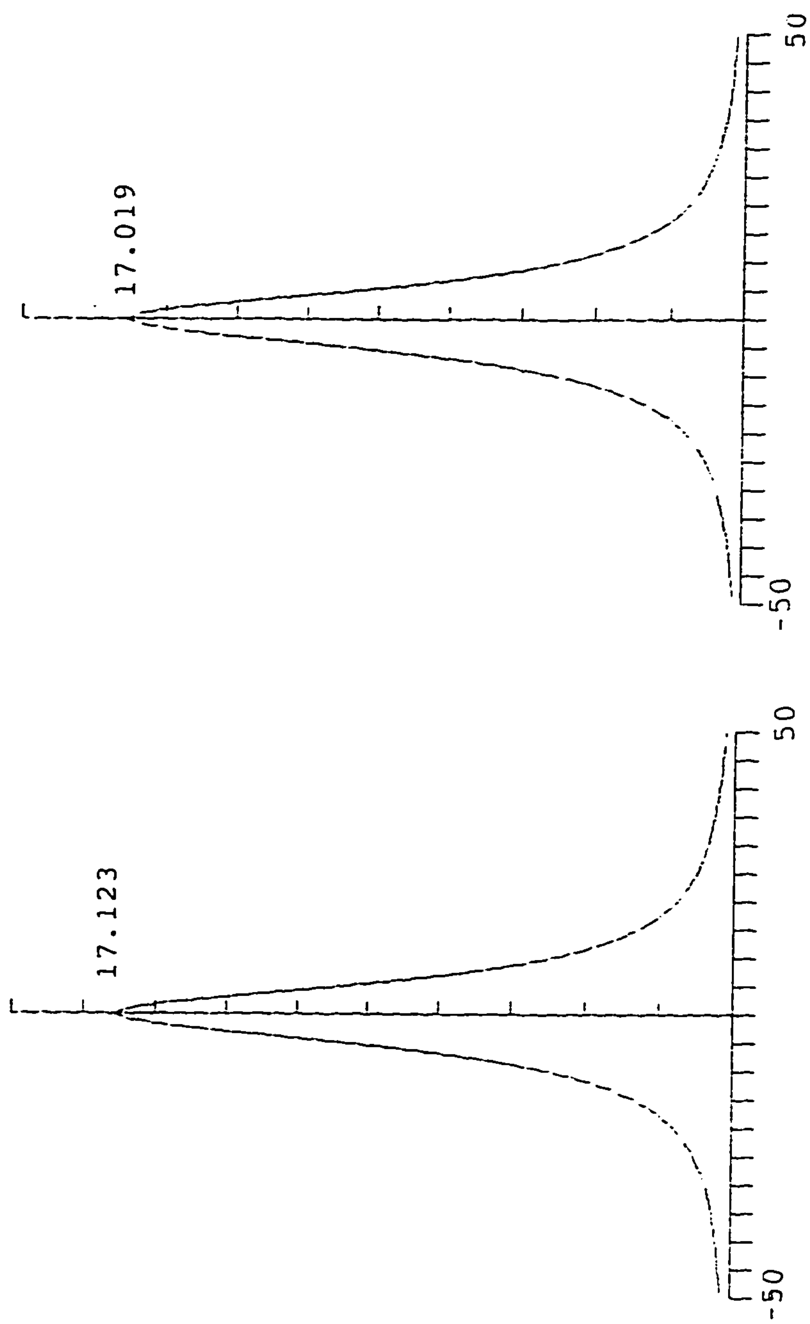


Figure 4.23: Plot for Flat configuration, Three Cables per phase. Cable dia. 1.20 inch (Single Phase Cable). Intermediate cases

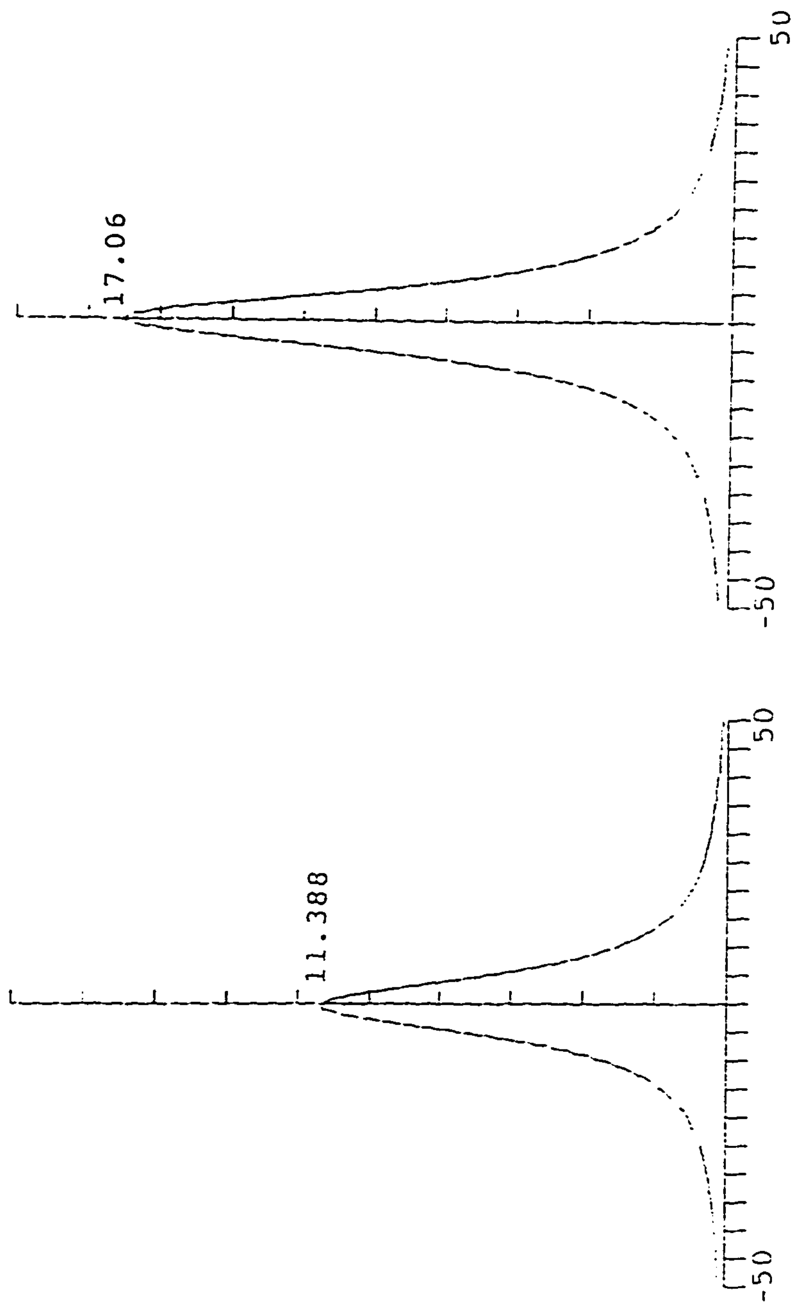


Figure 4.24: Plot for Flat configuration. Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

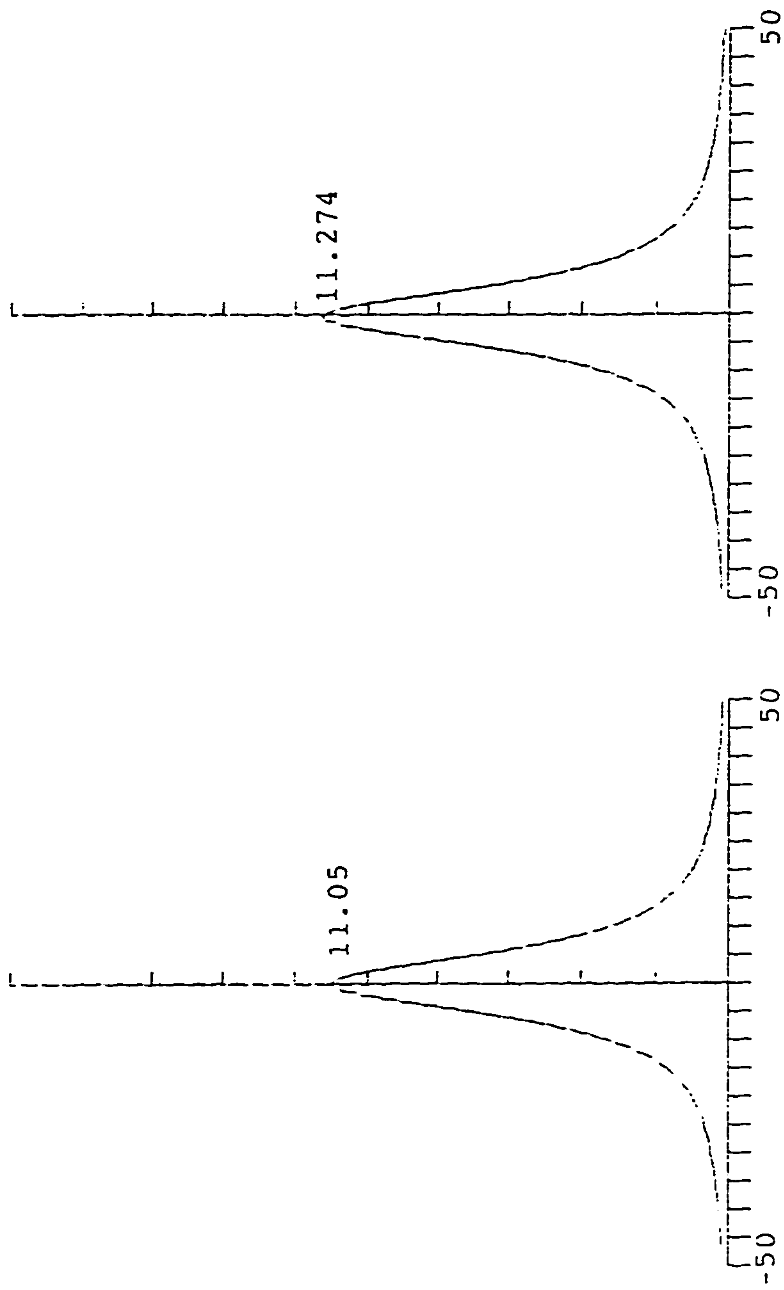


Figure 4.25: Plot for Flat configuration, Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

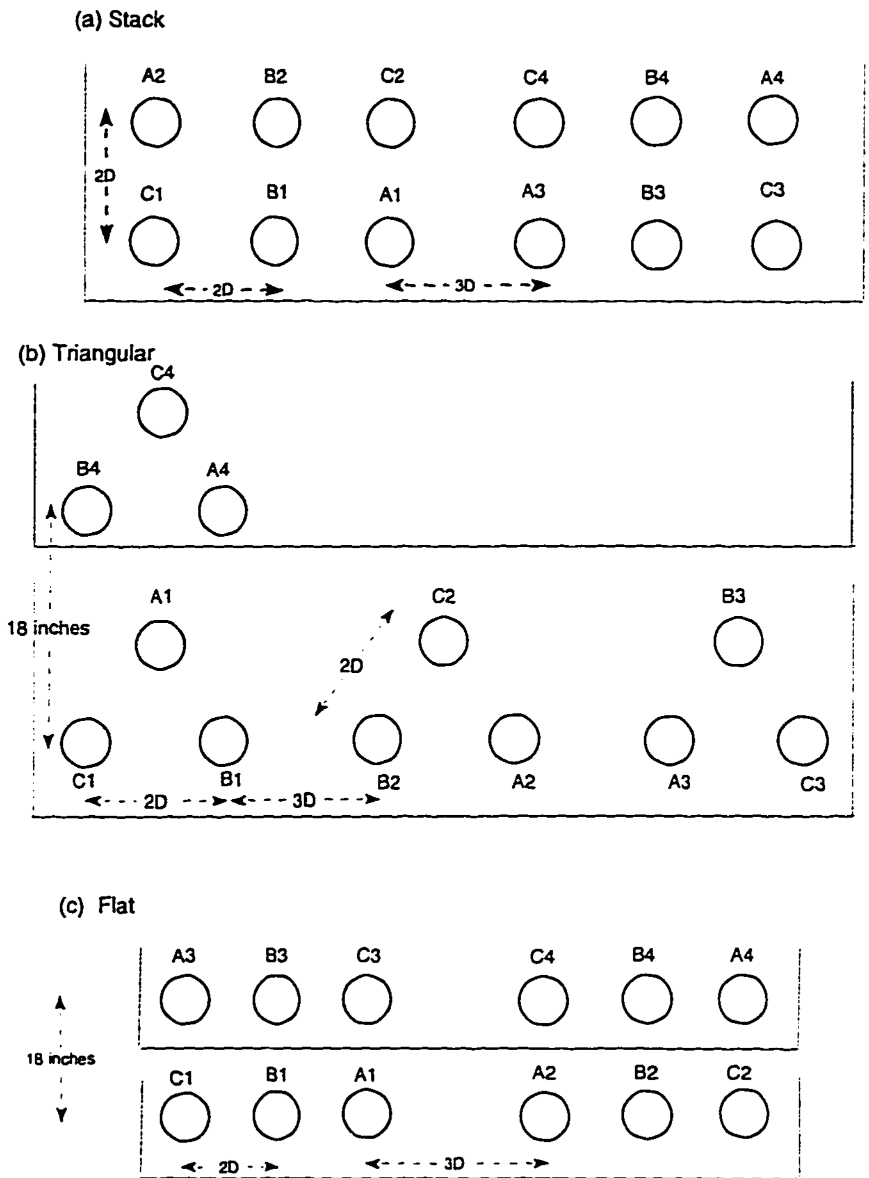


Figure 4.26: A conductor configuration with minimum field of four cables per phase (Single Phase Cable)

Table 4.7: Maximum Value of Magnetic Field obtained for four cables per phase(Single Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration Stack (mG)	Triangular (mG)	Flat (mG)
1.07	87.50	0.288	1.943	0.475
1.20	115.0	0.475	2.834	0.783
1.31	127.5	0.651	3.391	1.042
1.55	190.0	1.309	5.825	2.141
1.78	237.5	2.159	8.19	3.504
1.89	272.5	2.794	9.878	4.519

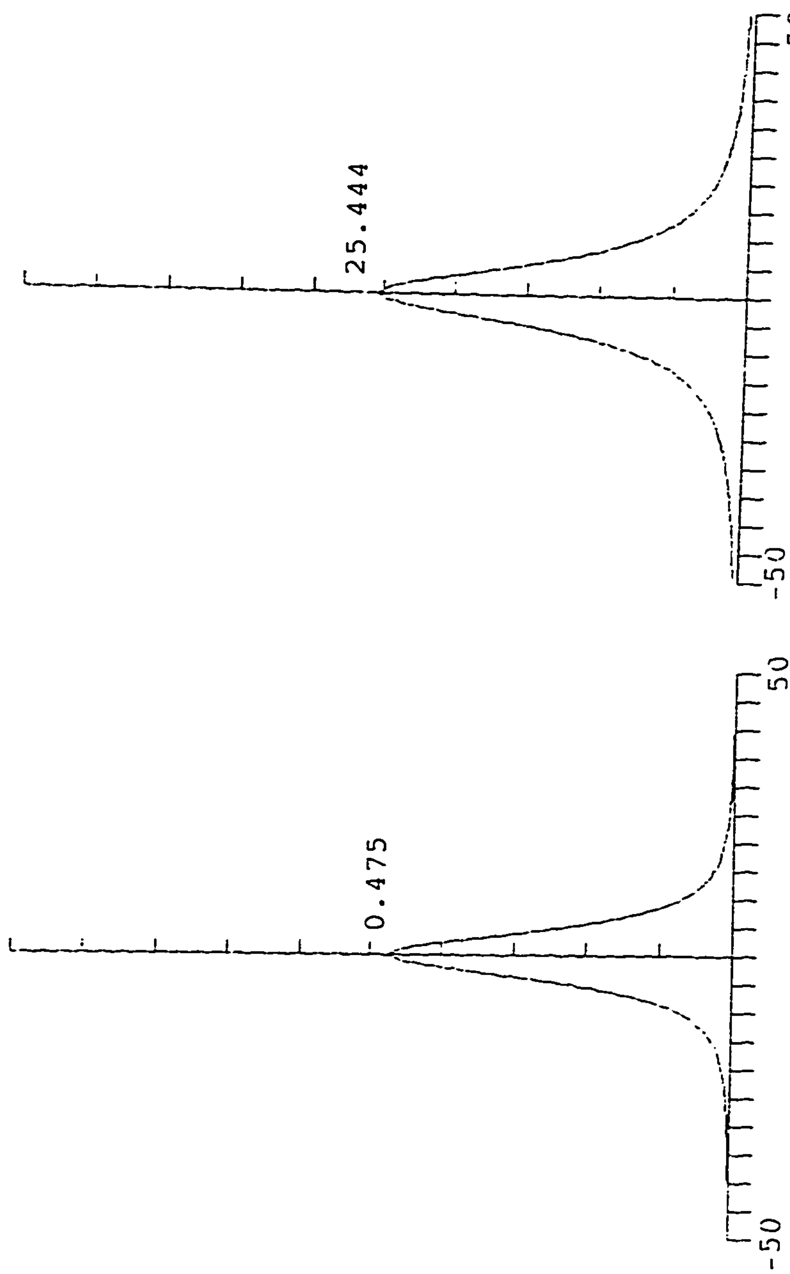


Figure 4.27: Plot for Stack configuration, Four Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

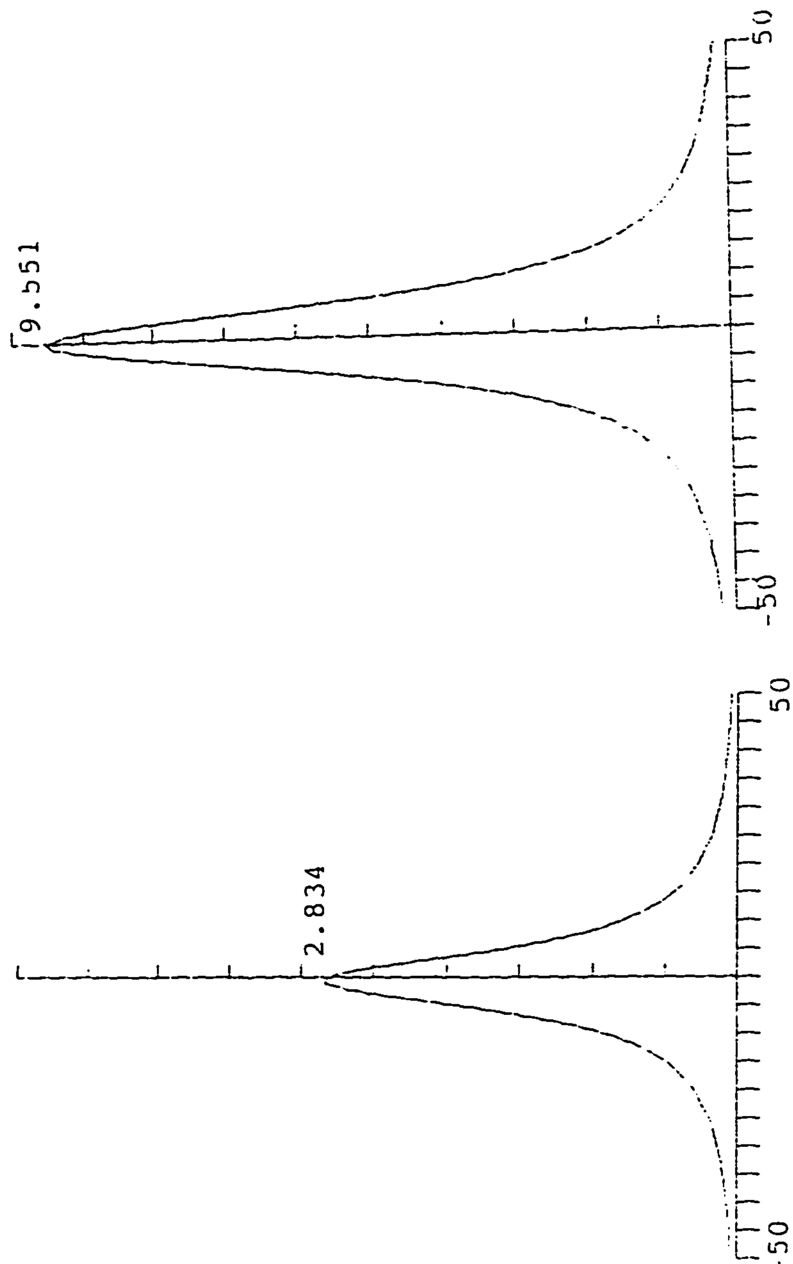


Figure 4.28: Plot for Triangular configuration. Four Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

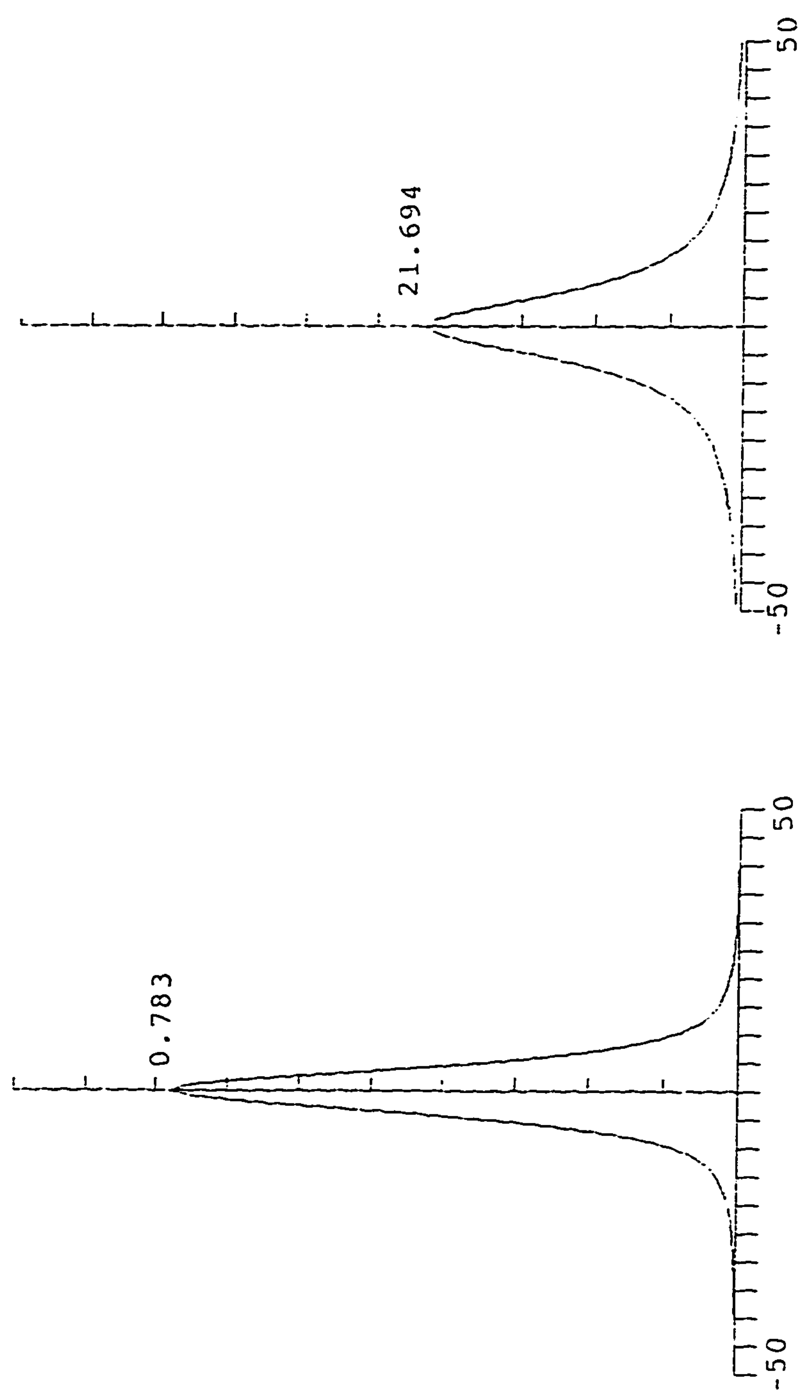


Figure 4.29: Plot for Flat configuration, Four Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

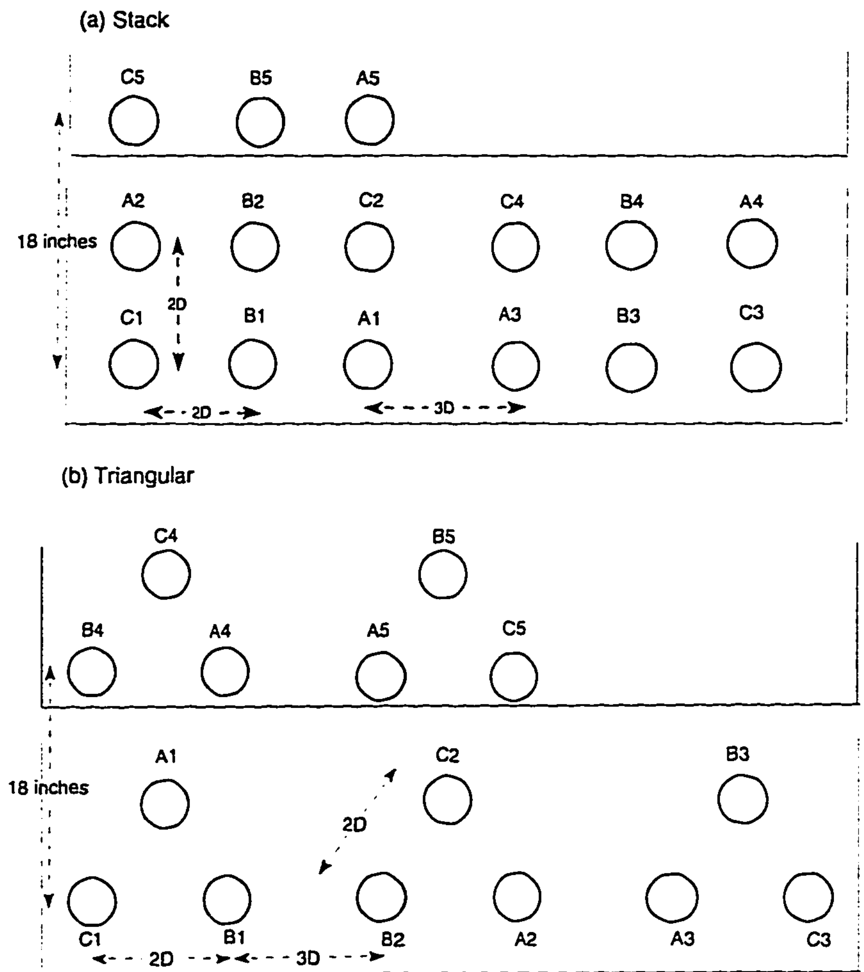
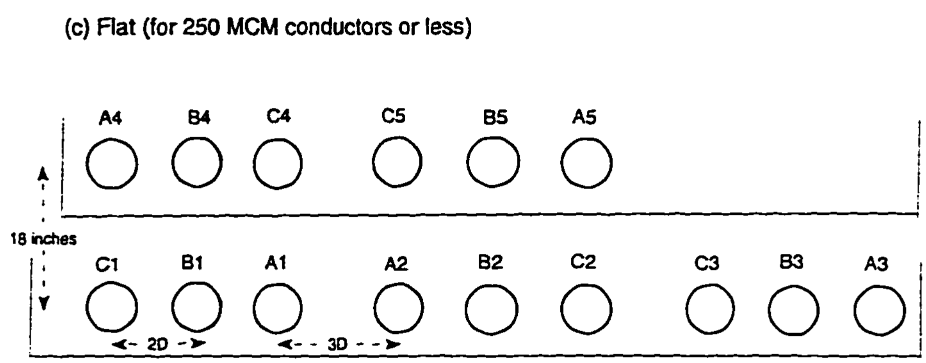


Figure 4.30: A conductor configuration with minimum field of five cables per phase (Single Phase Cable)



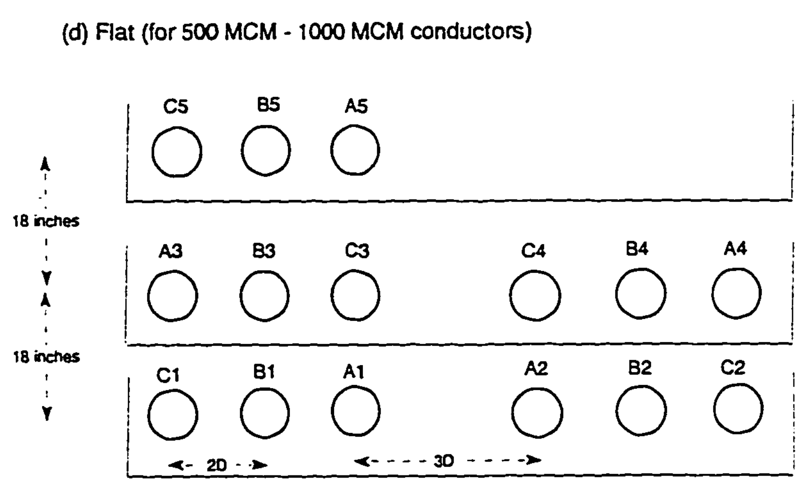


Figure 4.31: A conductor configuration with minimum field of five cables per phase (Single Phase Cable)

Table 4.8: Maximum Value of Magnetic Field obtained for five cables per phase(Single Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration Stack (mG)	Triangular (mG)	Flat (mG)
1.07	87.50	4.478	2.092	3.161
1.20	115.0	6.593	2.605	4.725
1.31	127.5	7.97	3.079	5.798
1.55	190.0	14.014	5.146	13.947
1.78	237.5	20.052	7.04	19.933
1.89	272.5	24.385	8.377	24.228

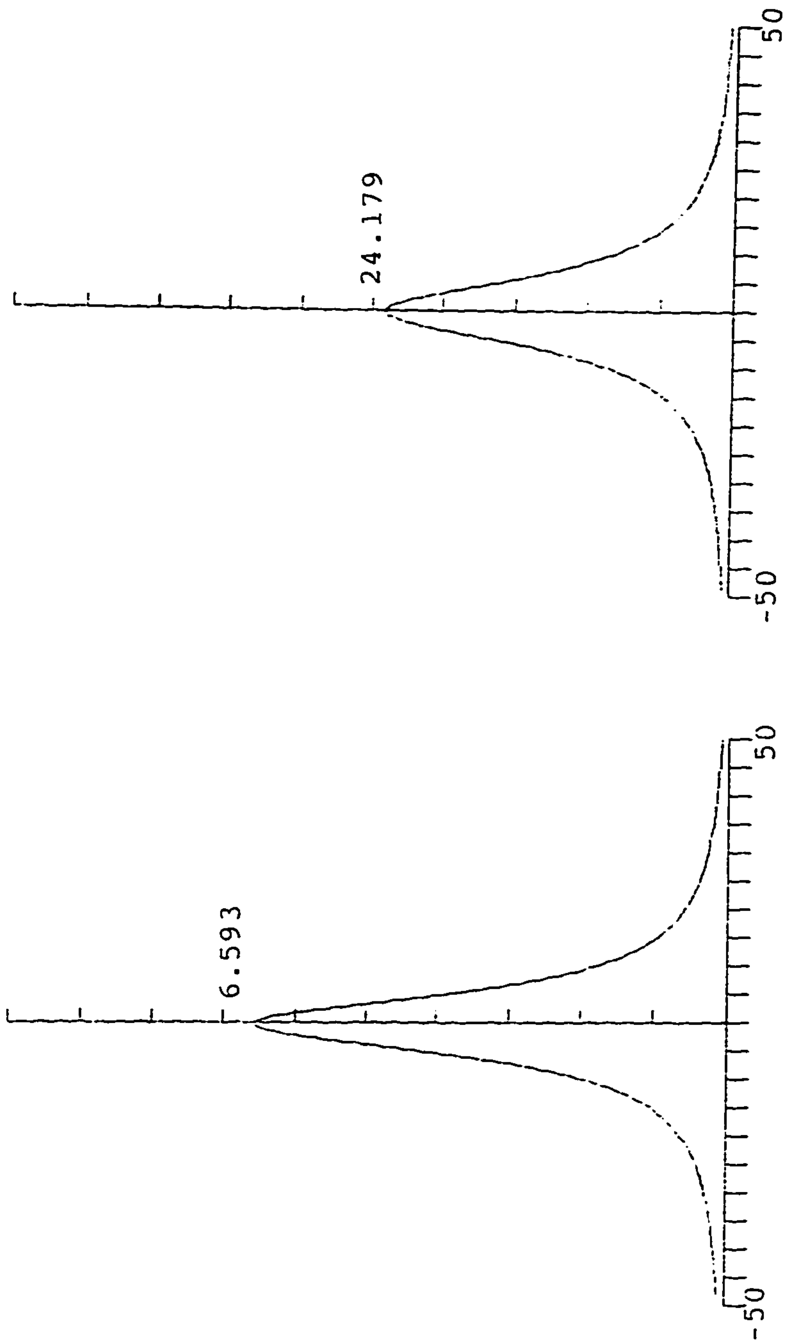


Figure 4.32: Plot for Stack configuration, Five Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

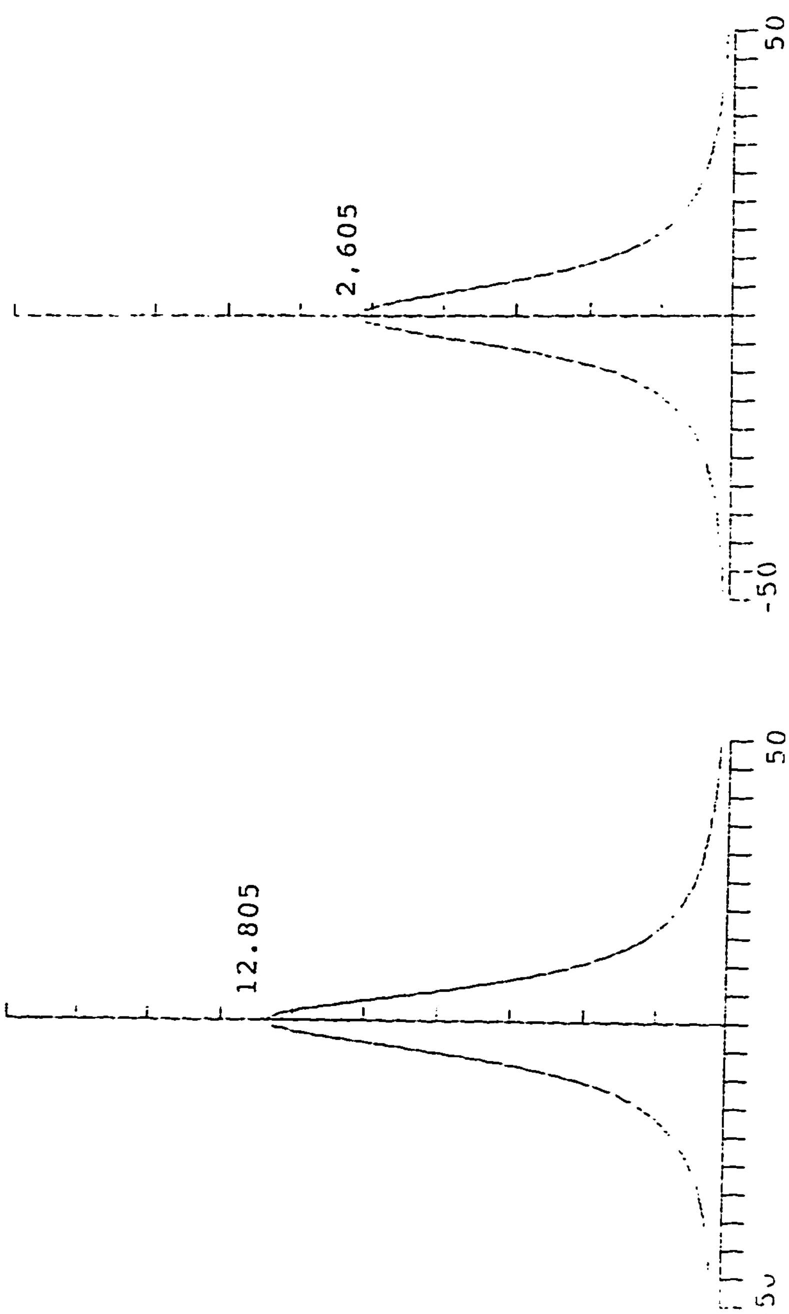


Figure 4.33: Plot for Traingular configuration. Five Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

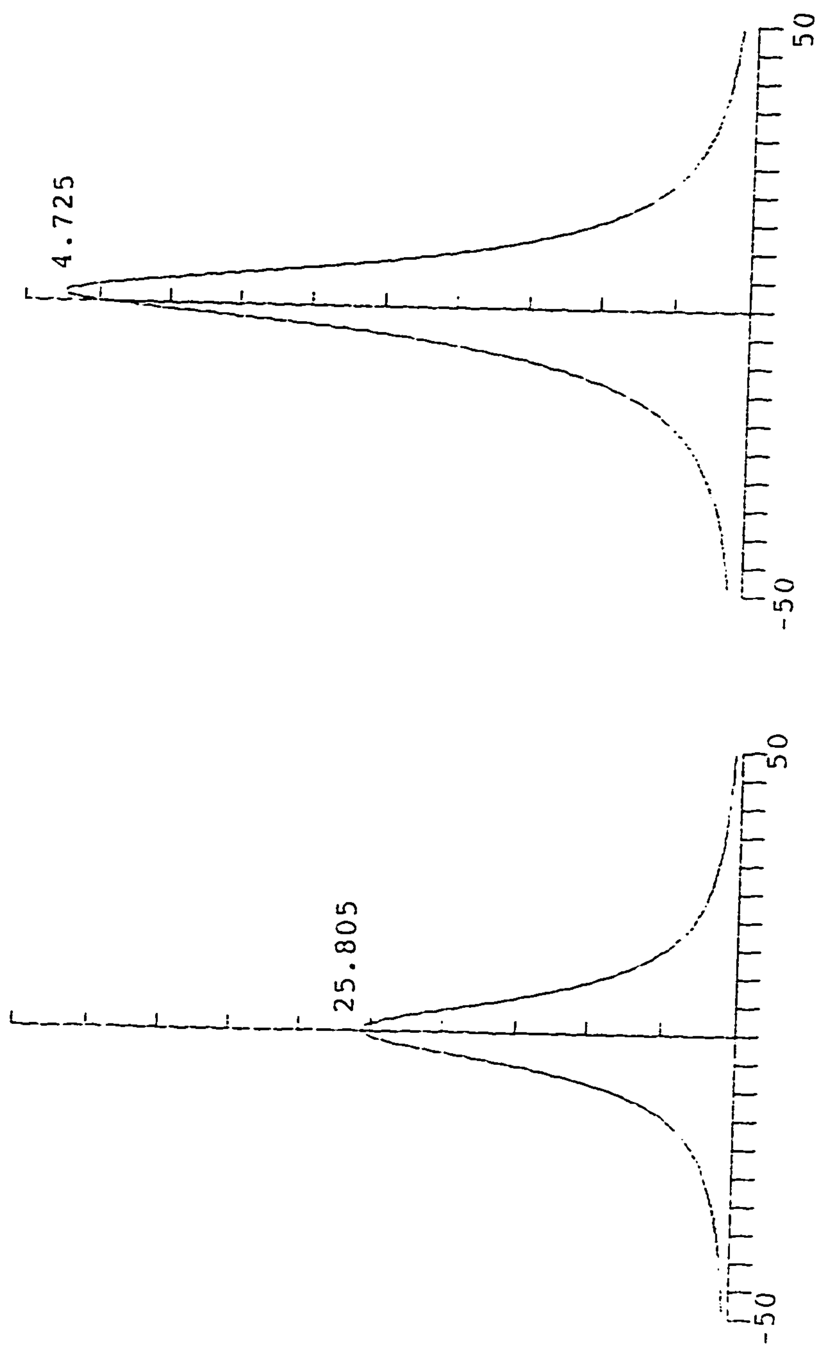
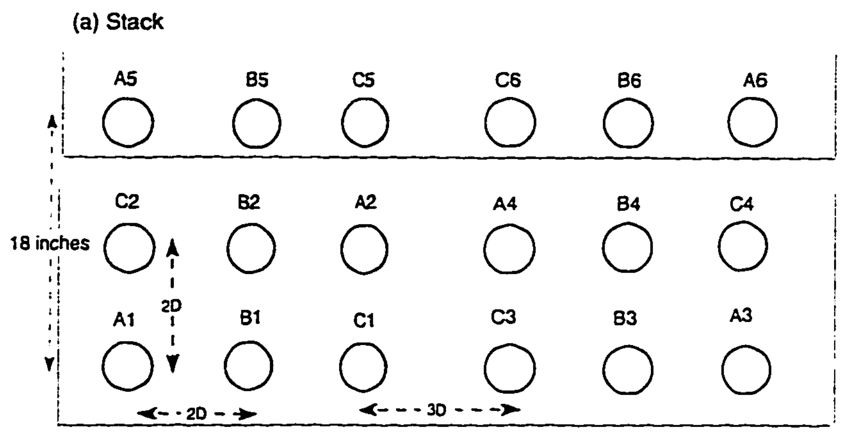


Figure 4.34: Plot for Flat configuration, Five Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case



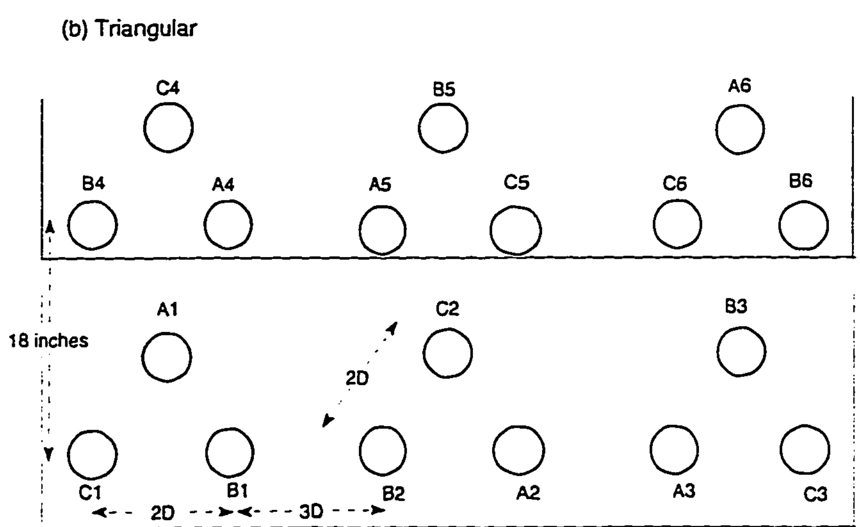


Figure 4.35: A conductor configuration with minimum field of six cables per phase (Single Phase Cable)

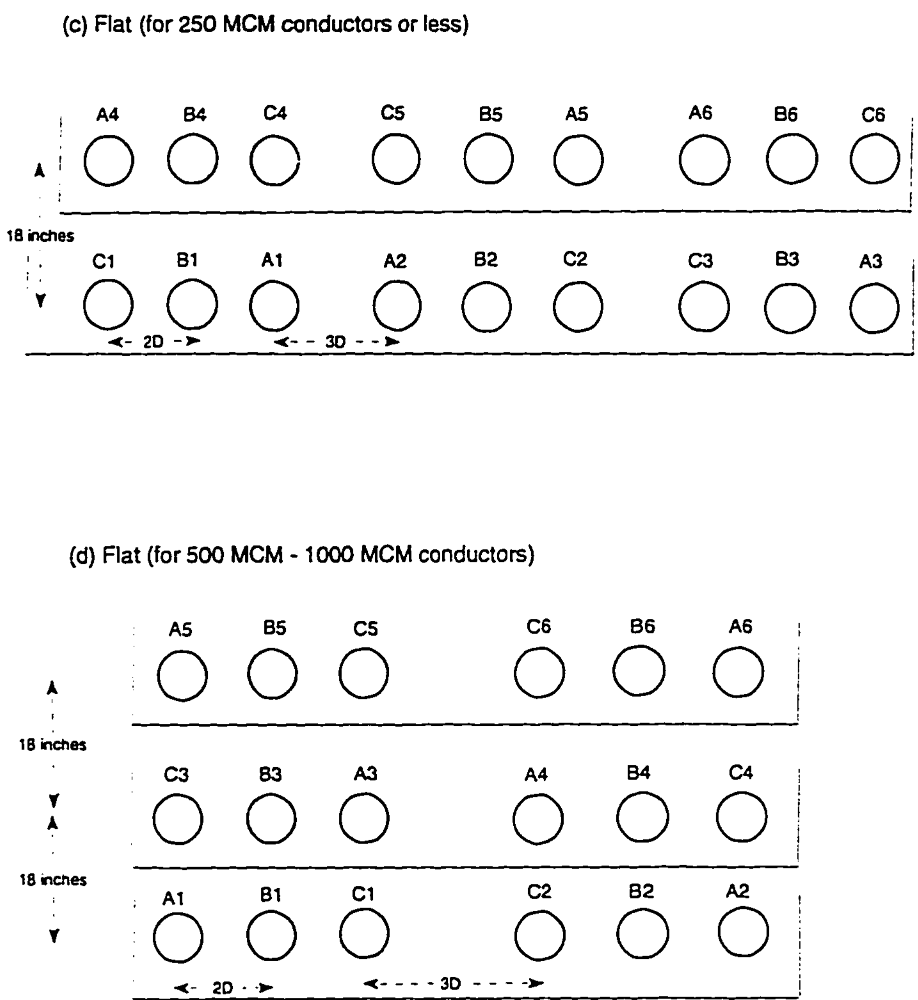


Figure 4.36: A conductor configuration with minimum field of six cables per phase (Single Phase Cable)

Table 4.9: Maximum Value of Magnetic Field obtained for six cables per phase(Single Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration Stack (mG)	Triangular (mG)	Flat (mG)
1.07	87.50	0.908	0.422	1.411
1.20	115.0	1.49	0.723	2.024
1.31	127.5	1.96	0.944	2.386
1.55	190.0	4.037	1.918	3.372
1.78	237.5	6.566	3.09	5.527
1.89	272.5	8.445	3.95	7.135

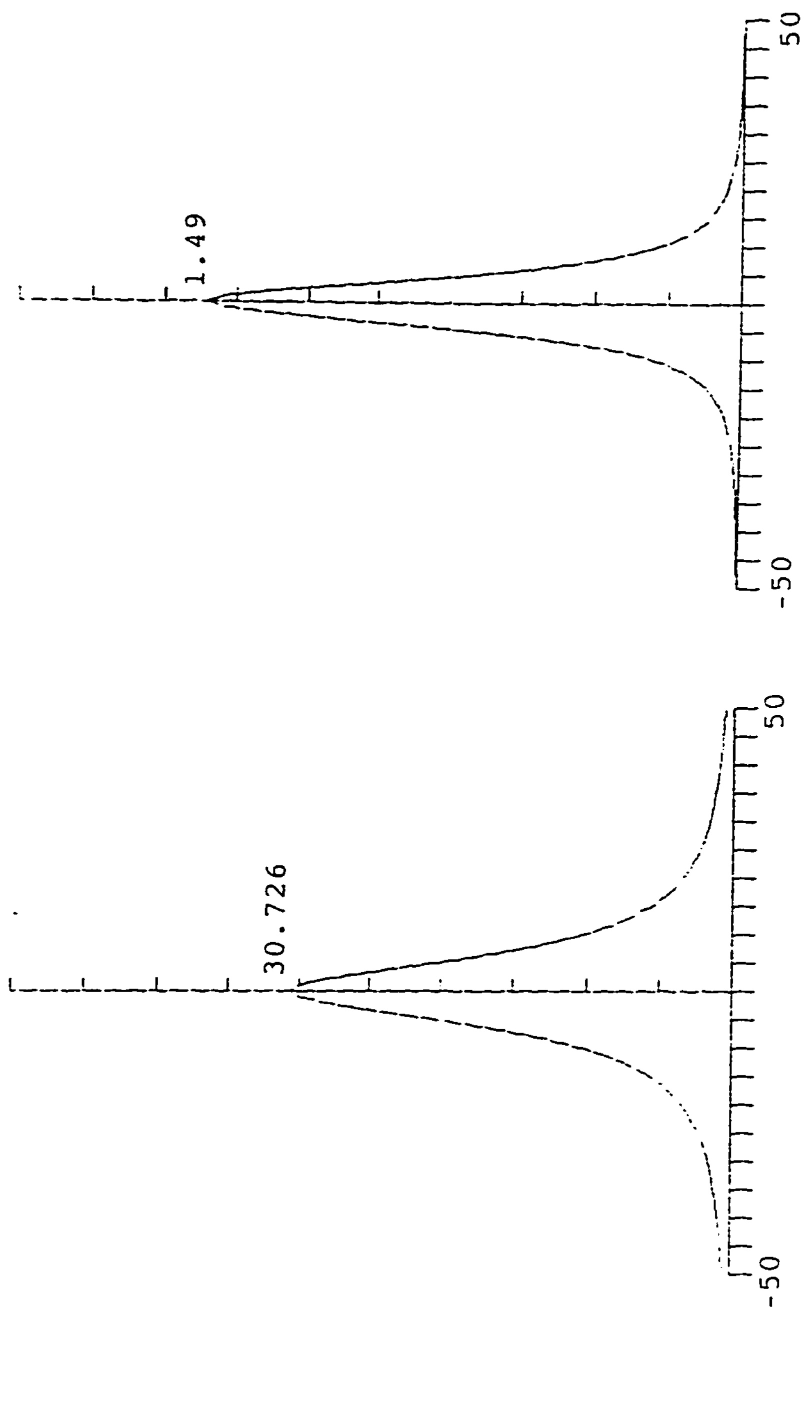


Figure 4.37: Plot for Stack configuration. Six Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

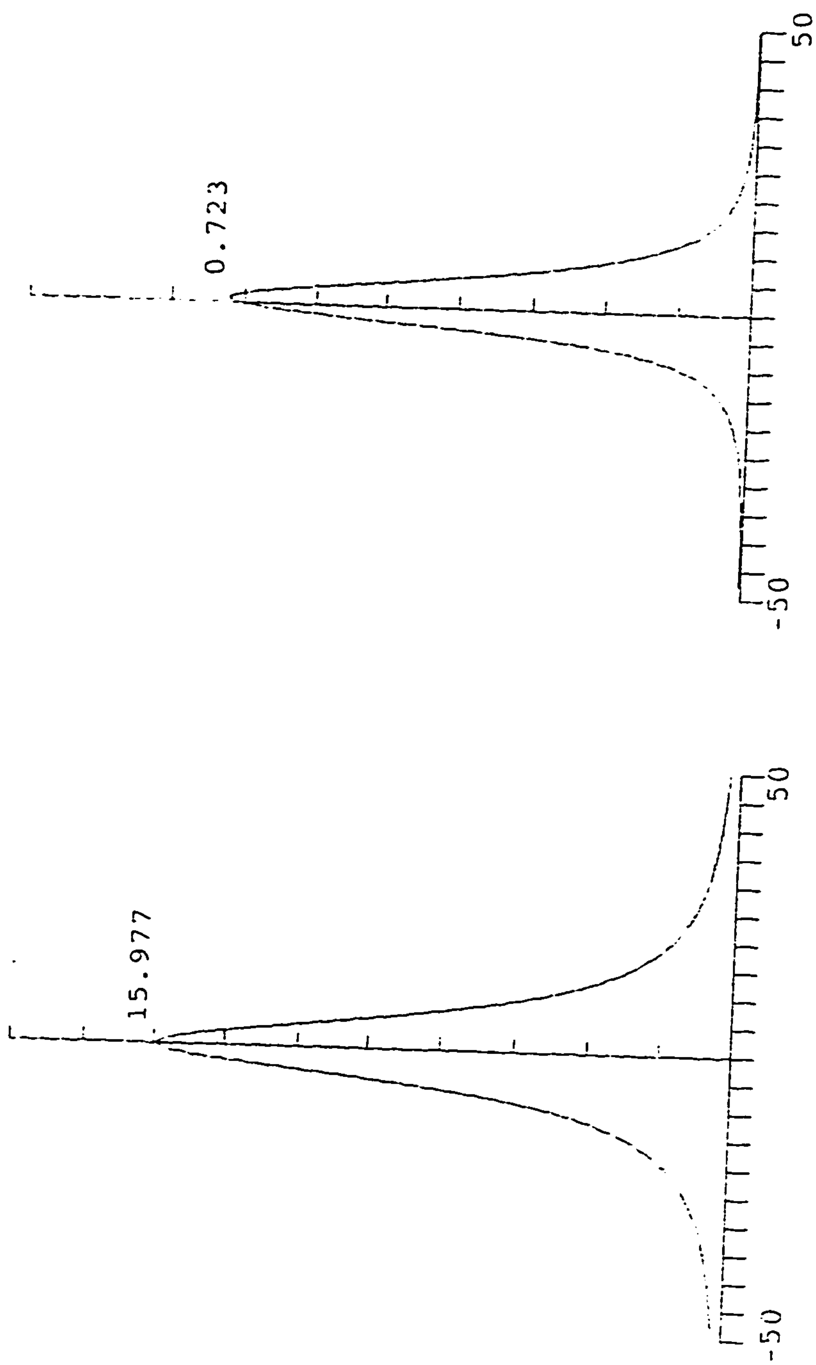


Figure 4.38: Plot for Triangular configuration, Six Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

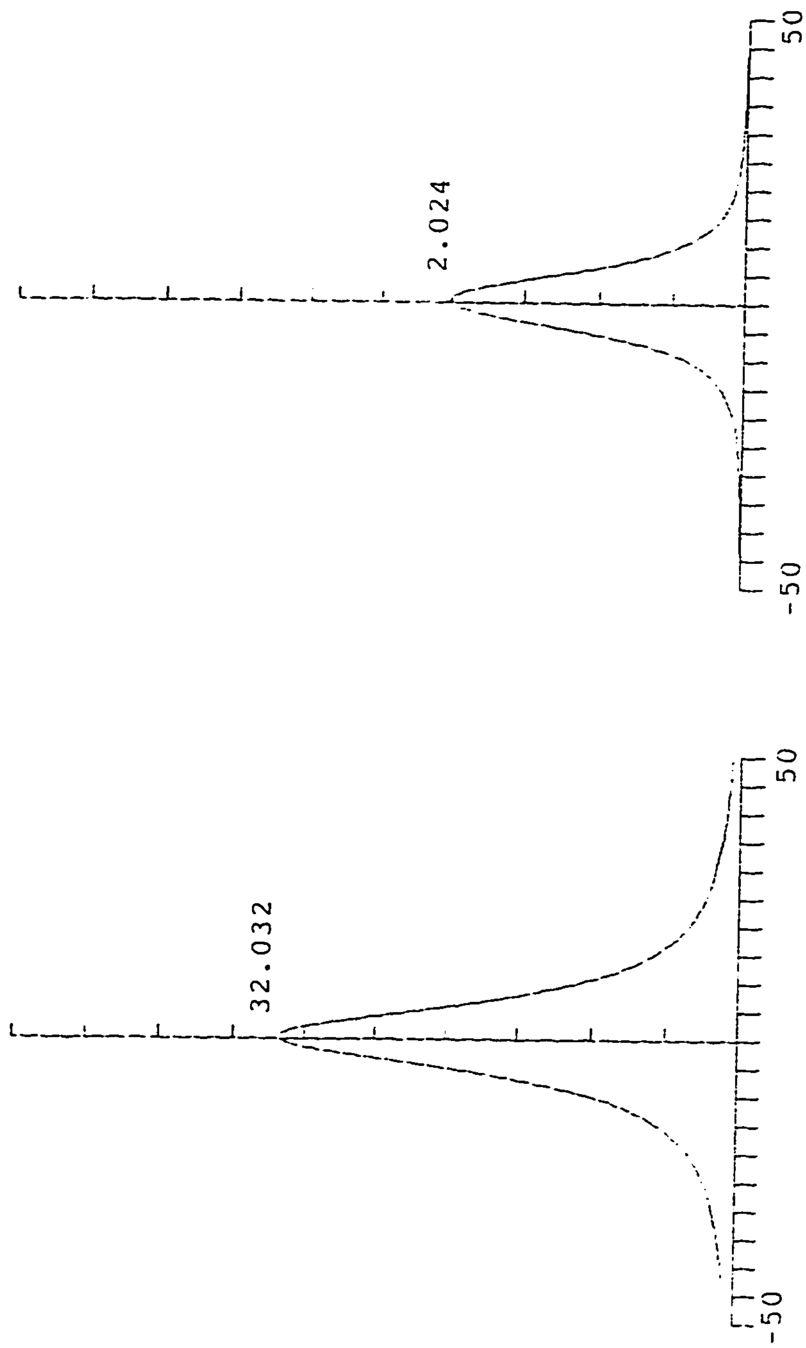


Figure 4.39: Plot for Flat configuration, Six Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

4.1.2 Simulation for three phase cables

In the case of three phase cable there are two cable configurations that are recommended by EPRI, namely the flat and the triangular configuration. The simulation is done for all the different cases which are simulated for a single phase cable. The depth of the uppermost conductor is taken as 36 inches. The effect of depth in management of fields is discussed in the next section.

In the case of a double circuit line (Fig.4.40) the field values for all the possible phase locations for the flat and the triangular layout are simulated and the results are tabulated in Table 4.10 and 4.11. The plots are shown in Figs.4.41 to 4.46. The comparison between the flat and the triangular cases for six different cable sizes are given in Table 4.12. For example, for a 1.55 inch dia. cable it is found to be only 1.456 mG for flat as compared to 6.349 mG for a triangular arrangement. So, there is 77 % reduction in the field if we use a flat configuration as compared to a triangular conductor arrangement.

For a three cables per phase (refer Fig. 4.47 circuit the triangular configuration is recommended as it gives a lesser field, the reduction being by a large amount. The field for same cable size in case of a flat configuration is approximately more than four times the field due to the flat. The results can be seen in Table 4.13. The layout of the conductor configuration for minimum field values is shown in Fig. 4.47.

When we have four cables per phase the recommended practice by EPRI for flat is to have three conductors in one tray and the other nine in other tray (refer Fig. 4.48). The field is more in case of a triangular configuration because all the cables are in one tray at a depth of 36 inches from ground, whereas, for flat configuration the lower tray depth is more by 18 inches as compared to the upper tray and we have more conductors in the lower one. Hence, due to increased distance the field is lower. Fields for all the six cable sizes are given in Table 4.14.

There are two types of layout for triangular configuration in the case of five and six cables per phase. For cables size from 2/0 to 250MCM all the conductors are in one tray. The results obtained by simulation are given in Tables 4.15 and 4.16, whereas, the drawings are shown in Figs.4.49 to 4.50. For five cables per phase the flat configuration is preferable due to lower field values for all the cable sizes considered. However, for six cables per phase the flat arrangement gives lower field than the triangular for smaller size cables (up to 250 MCM) but for large cable sizes (500 MCM and more) the triangular configuration is recommended.

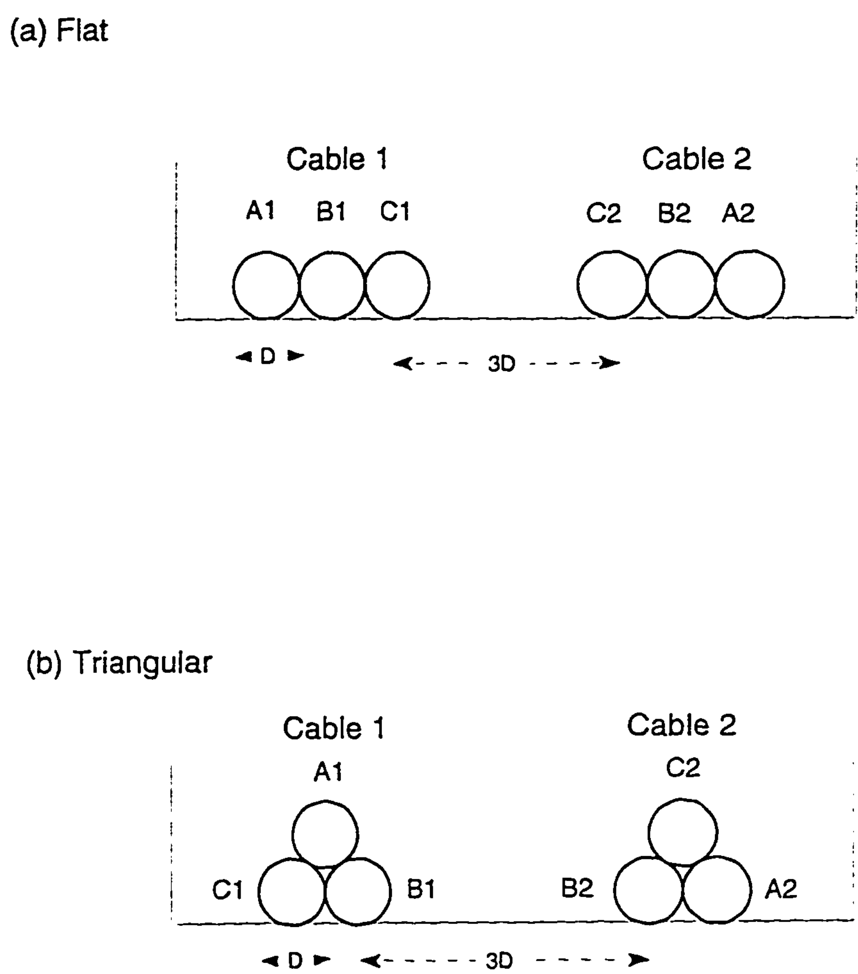


Figure 4.40: A conductor configuration with minimum field of two cables per phase (Three Phase Cable)

Table 4.10: Max. magnetic field values (mG) for all possible phase locations for a Flat Conguration, 2 Cables per phase, (Cable dia.= 1.20 inch, Three Phase Cable)

abc abc (6.593)	abc acb (5.71)	abc cab (3.29)	abc cba (0.529)	abc bca (3.303)	abc bac (5.71)
acb abc (5.71)	acb acb (6.593)	acb cab (5.71)	acb cba (5.71)	acb bca (0.529)	acb bac (3.29)
cab abc (3.303)	cab acb (5.71)	cab cab (6.593)	cab cba (5.71)	cab bca (3.29)	cab bac (0.529)
cba abc (0.529)	cba acb (3.29)	cba cab (5.71)	cba cba (6.593)	cba bca (5.71)	cba bac (3.303)
bca abc (3.29)	bca acb (0.529)	bca cab (3.303)	bca cba (5.71)	bca bca (6.593)	bca bac (5.71)
bac abc (5.71)	bac acb (3.303)	bac cab (0.529)	bac cba (3.29)	bac bca (5.71)	bac bac (6.593)

Table 4.11: Max. magnetic field values (mG) for all possible phase locations for a Triangular Configuration, 2 Cables per phase (Cable dia.= 1.20 inch, Three Phase Cable)

a a c b c b (6.447)	a a c b b c (6.45)	a c c b b a (3.053)	a c c b a b (4.22)	a b c b a c (3.394)	a b c b c a (4.22)
a a b c c b (6.45)	a a b c b c (6.447)	a c b c b a (4.22)	a c b c a b (3.394)	a b b c a c (4.22)	a b b c c a (3.053)
c a b a c b (3.394)	c a b a b c (4.22)	c c b a b a (6.447)	c c b a a b (6.45)	c b b a a c (3.053)	c b b a c a (4.22)
c a a b c b (4.22)	c a a b b c (3.053)	c c a b b a (6.45)	c c a b a b (6.447)	c b a b a c (4.22)	c b a b c a (3.394)
b a a c c b (3.053)	b a a c b c (4.22)	b c a c b a (3.394)	b c a c a b (4.22)	b b a c a c (6.447)	b b a c c a (6.45)
b a c a c b (4.22)	b a c a b c (3.394)	b c c a b a (4.22)	b c c a a b (3.053)	b b c a a c (6.45)	b b c a c a (6.447)

Table 4.12: Maximum Value of Magnetic Field obtained for two cables per phase(Three Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration	
		Flat (mG)	Triangular (mG)
1.07	87.50	0.321	2.087
1.20	115.0	0.529	3.053
1.31	127.5	0.7	3.67
1.55	190.0	1.456	6.349
1.78	237.5	2.393	8.976
1.89	272.5	2.698	10.85

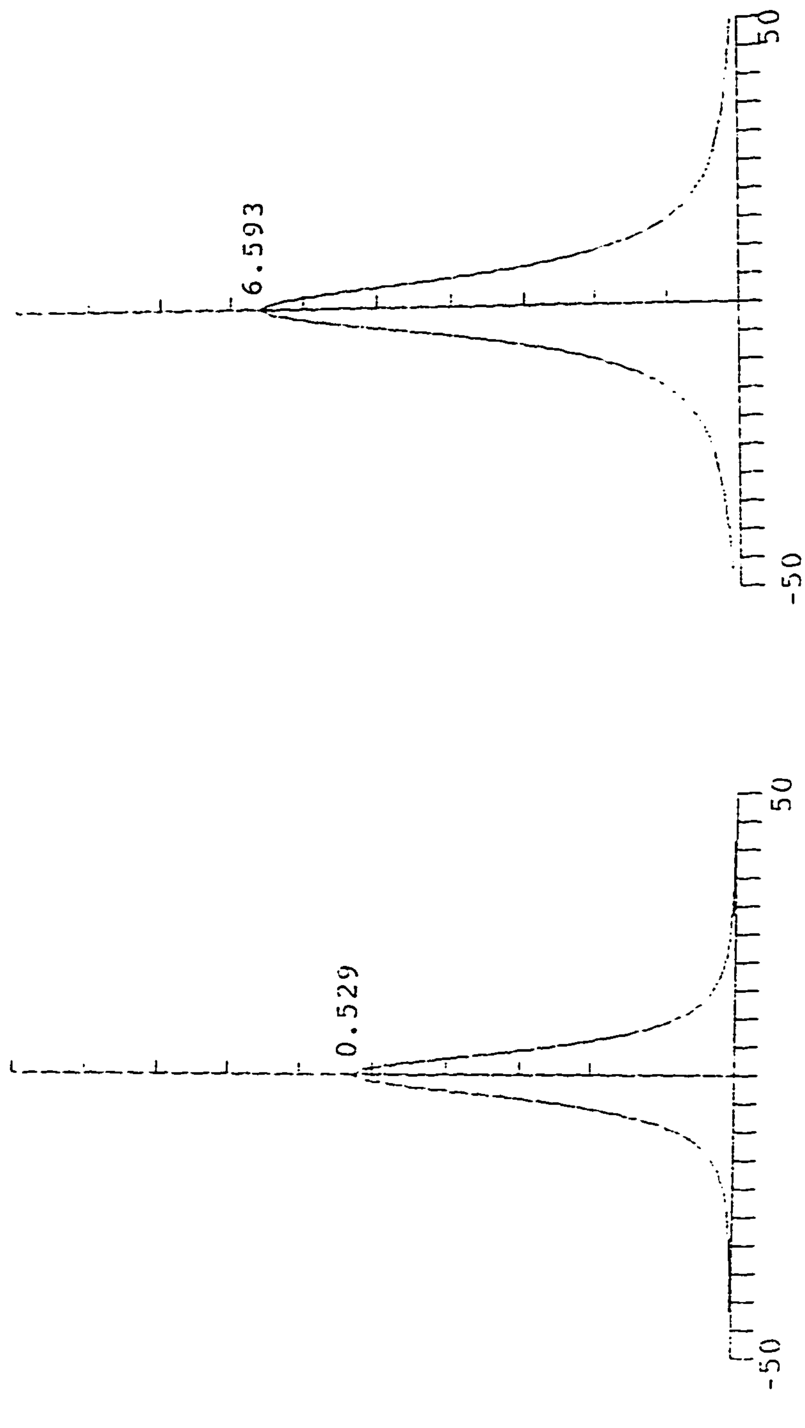


Figure 4.41: Plot for Flat configuration. Two Cables per phase. Cable dia. 1.20 inch (Three Phase Cable). Best and Worst case

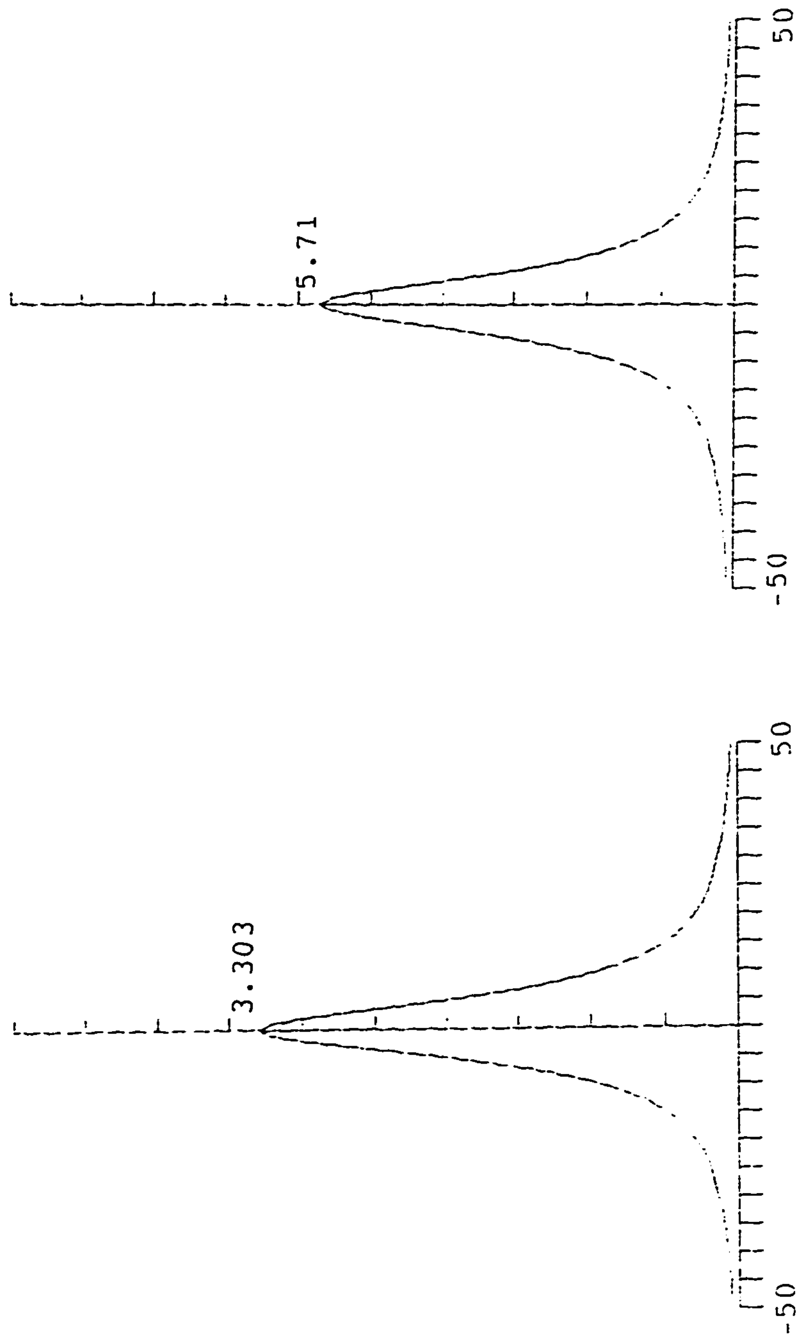


Figure 4.42: Plot for Flat configuration, Two Cables per phase, Cable dia. 1.20 inch (Three Phase Cable), Intermediate cases

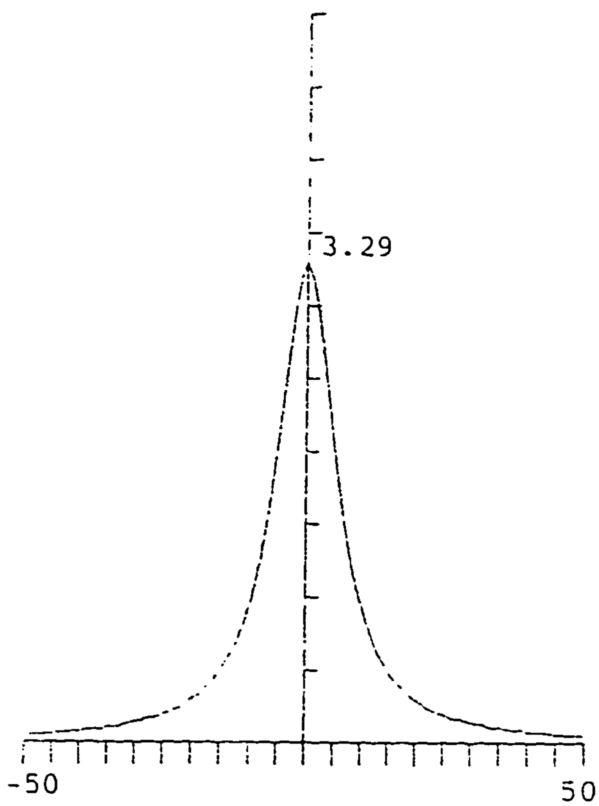


Figure 4.43: Plot for Flat configuration, Two Cables per phase. Cable dia. 1.20 inch (Three Phase Cable), Intermediate cases

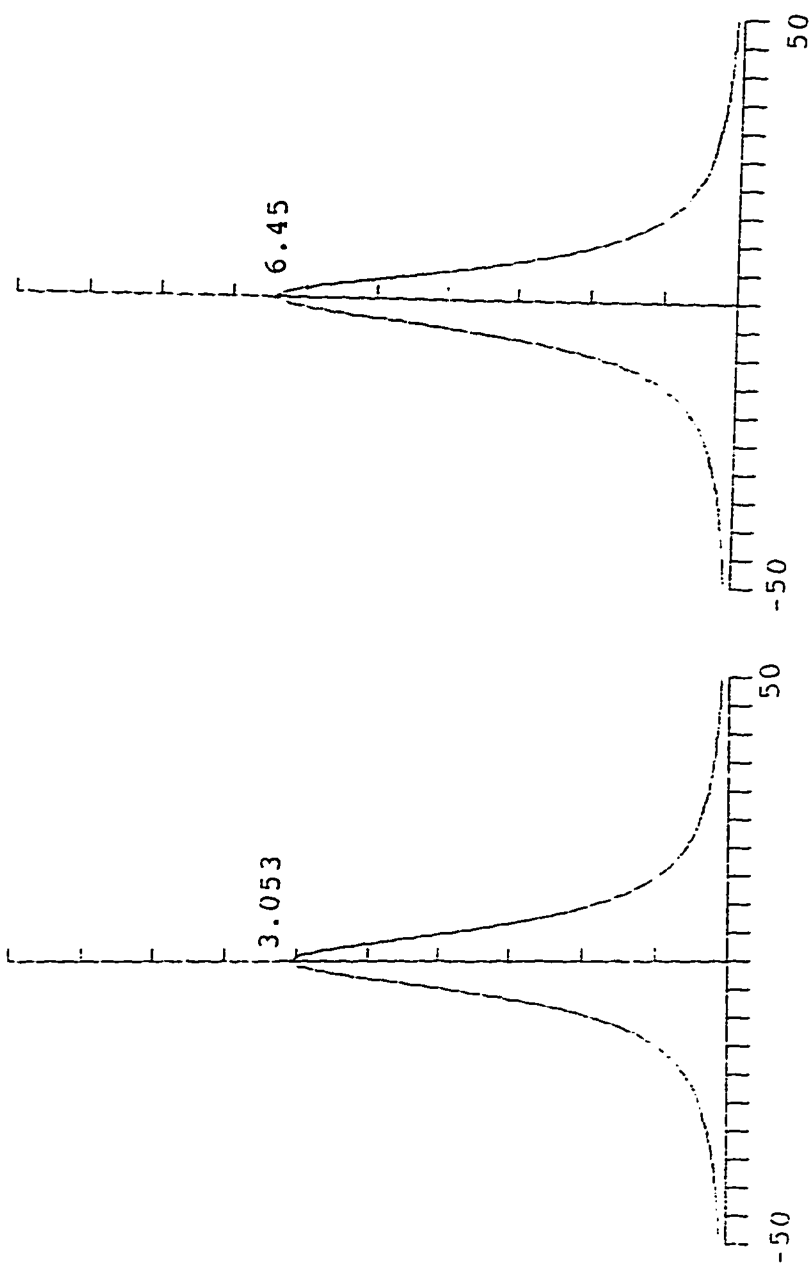


Figure 4.44: Plot for Triangular configuration, Two Cables per phase, Cable dia. 1.20 inch (Three Phase Cable), Best and Worst case

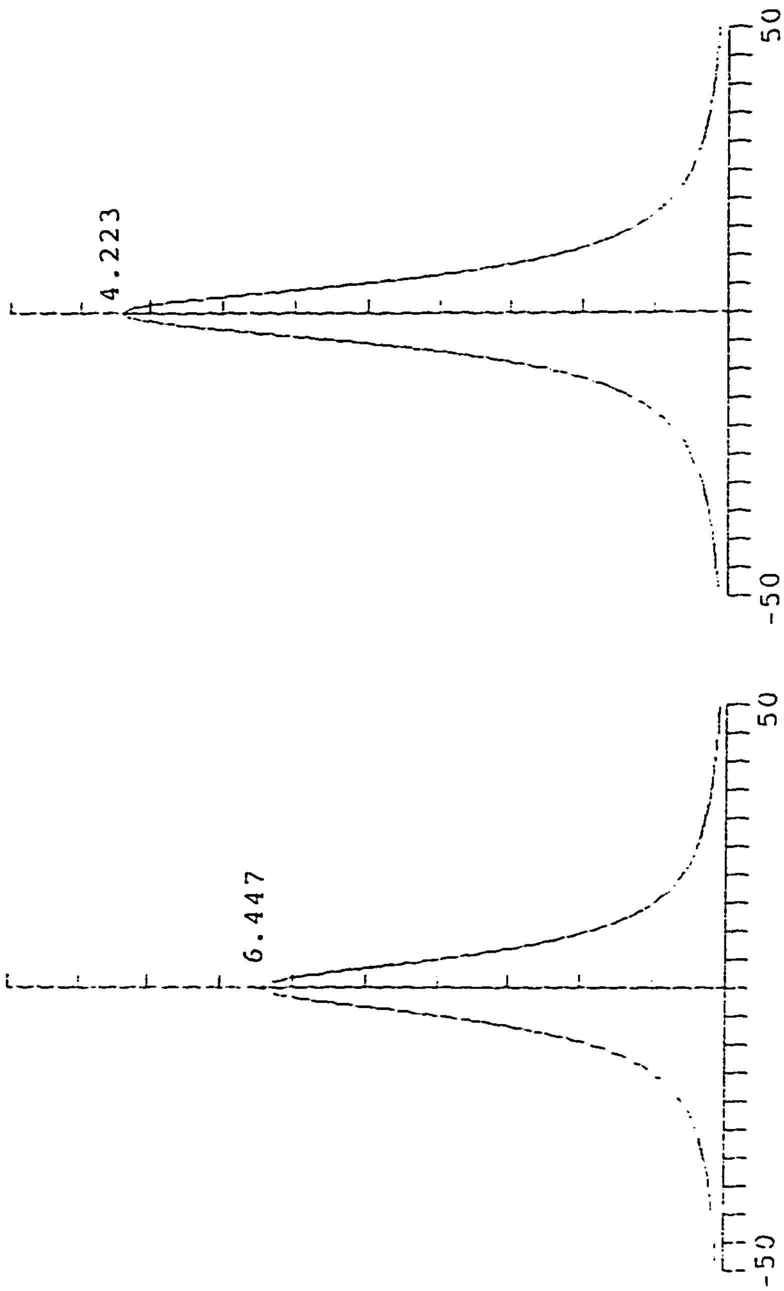


Figure 4.45: Plot for Triangular configuration, Two Cables per phase, Cable dia. 1.20 inch (Three Phase Cable), Intermediate cases

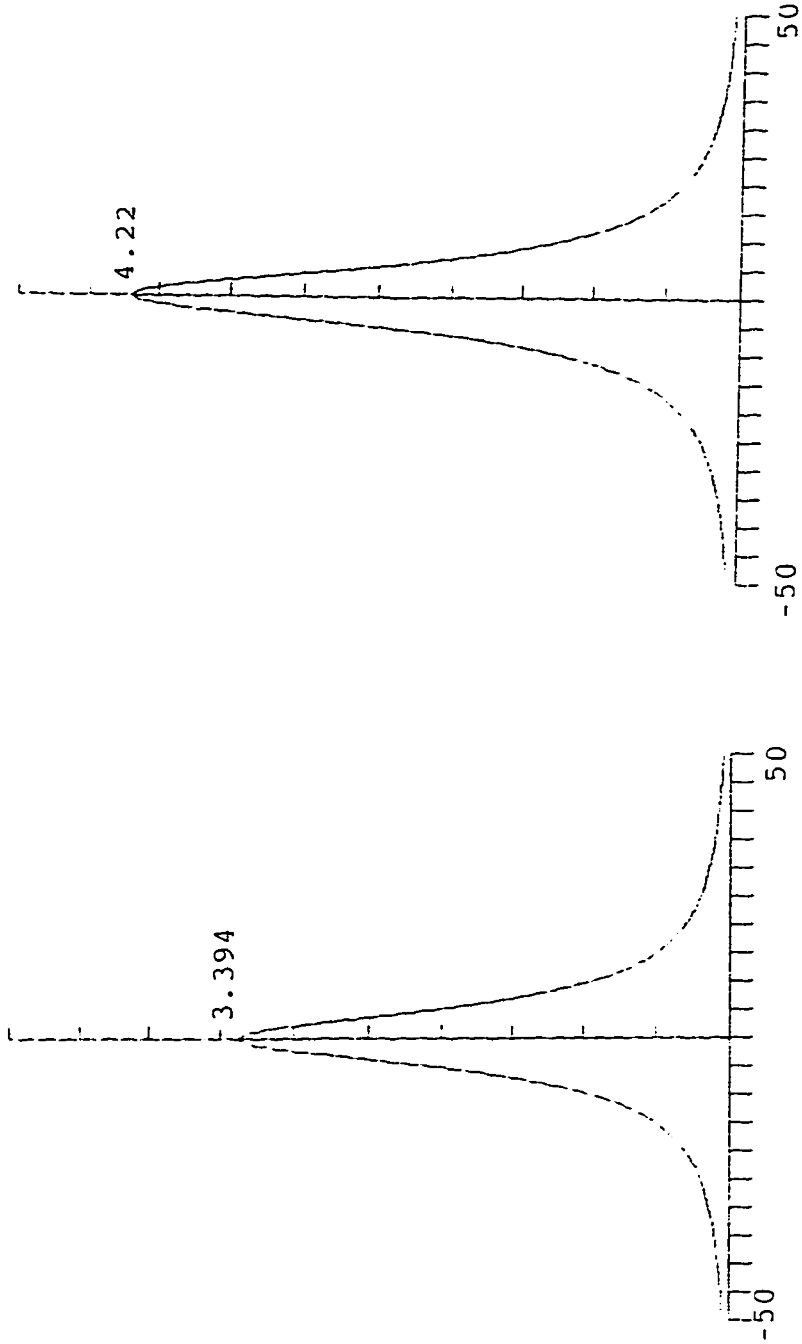


Figure 4.46: Plot for Triangular configuration. Two Cables per phase. Cable dia. 1.20 inch (Three Phase Cable), Intermediate cases

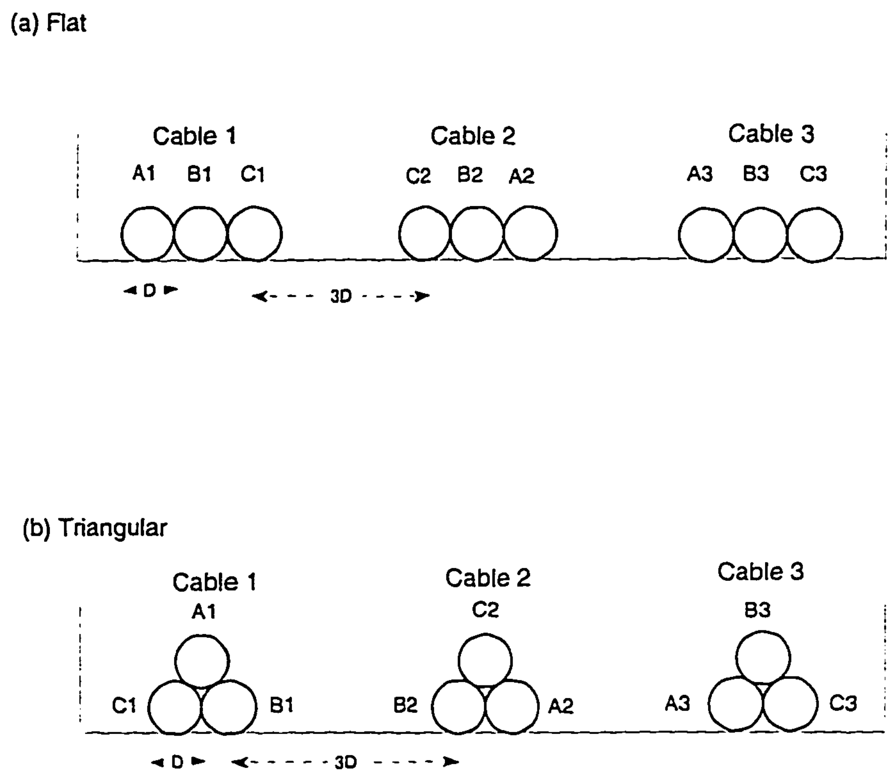


Figure 4.47: A conductor configuration with minimum field of three cables per phase (Three Phase Cable)

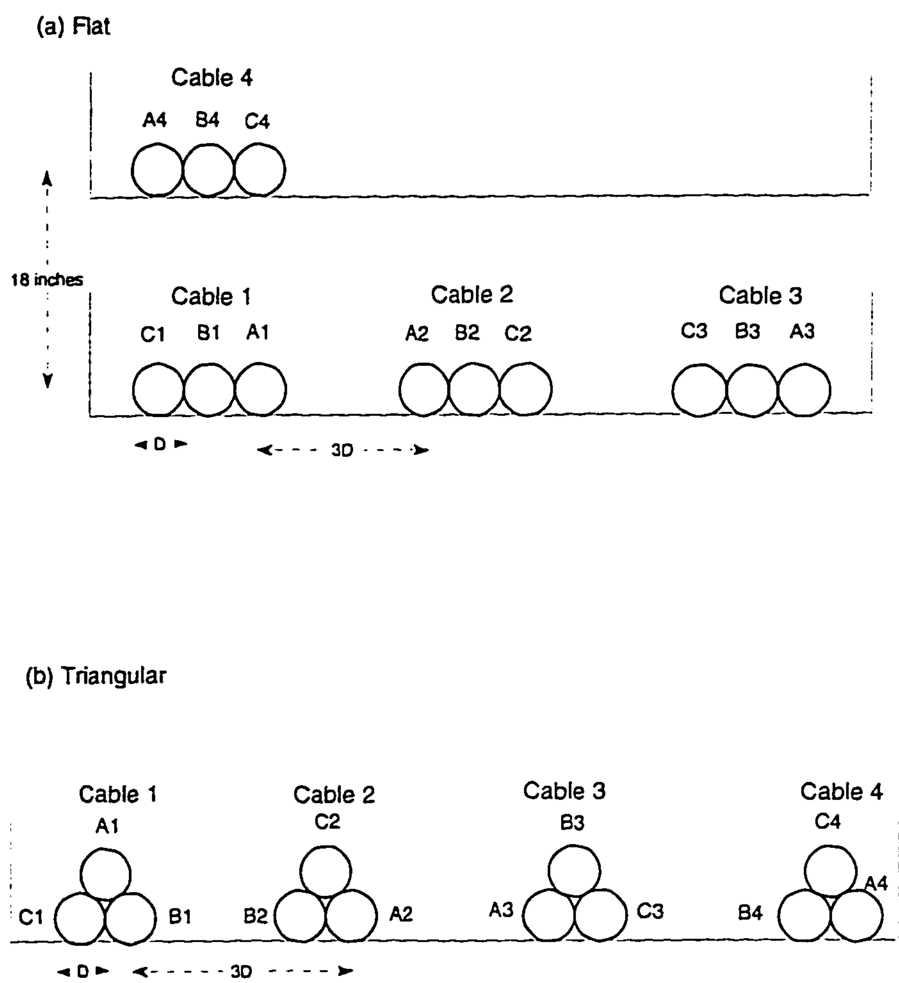


Figure 4.48: A conductor configuration with minimum field of four cables per phase (Three Phase Cable)

Table 4.13: Maximum Value of Magnetic Field obtained for three cables per phase(Three Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration Flat (mG)	Triangular (mG)
1.07	87.50	2.18	0.394
1.20	115.0	3.188	0.681
1.31	127.5	3.829	0.865
1.55	190.0	6.627	1.788
1.78	237.5	9.315	2.973
1.89	272.5	11.223	3.756

Table 4.14: Maximum Value of Magnetic Field obtained for four cables per phase(Three Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration Flat (mG)	Triangular (mG)
1.07	87.50	0.84	2.025
1.20	115.0	1.258	2.972
1.31	127.5	1.545	3.578
1.55	190.0	2.817	6.232
1.78	237.5	4.185	8.891
1.89	272.5	5.185	10.804

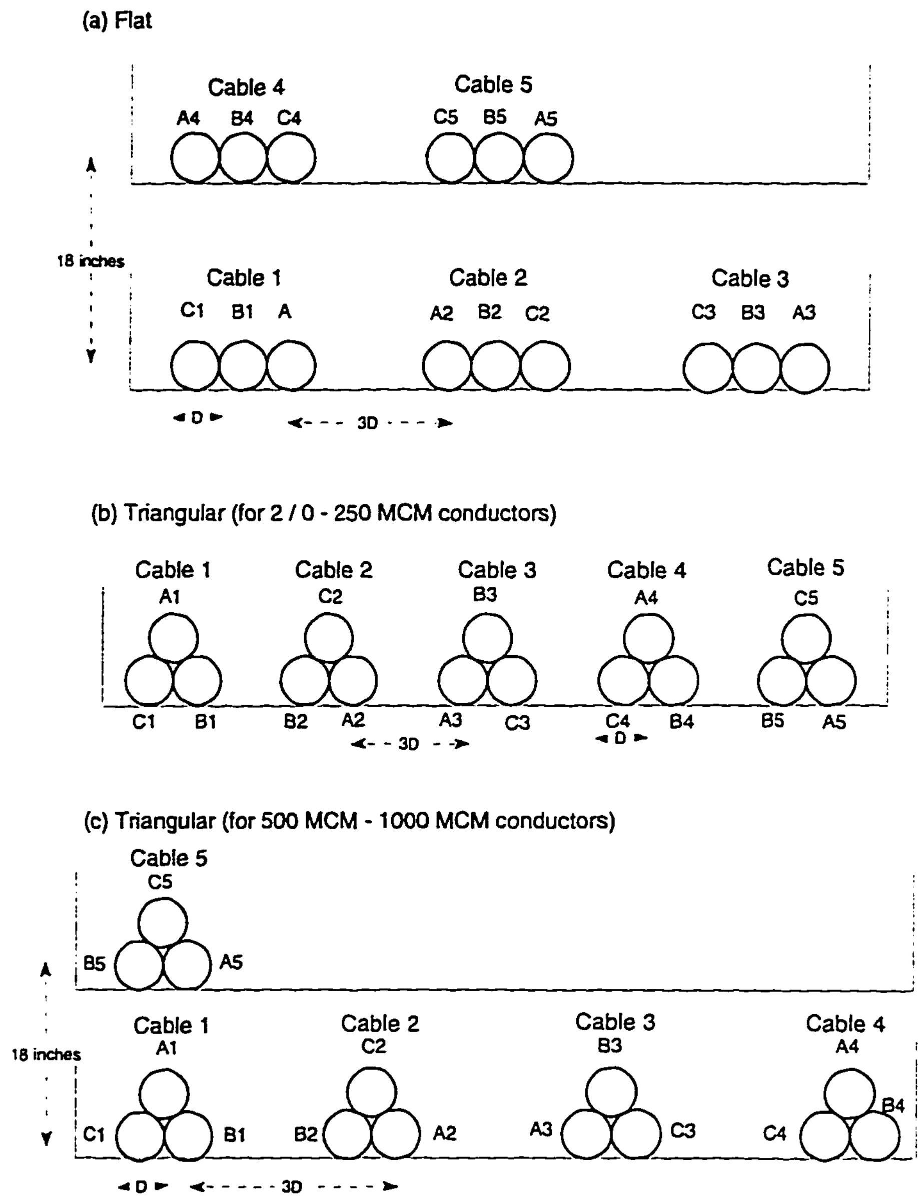


Figure 4.49: A conductor configuration with minimum field of five cables per phase (Three Phase Cable)

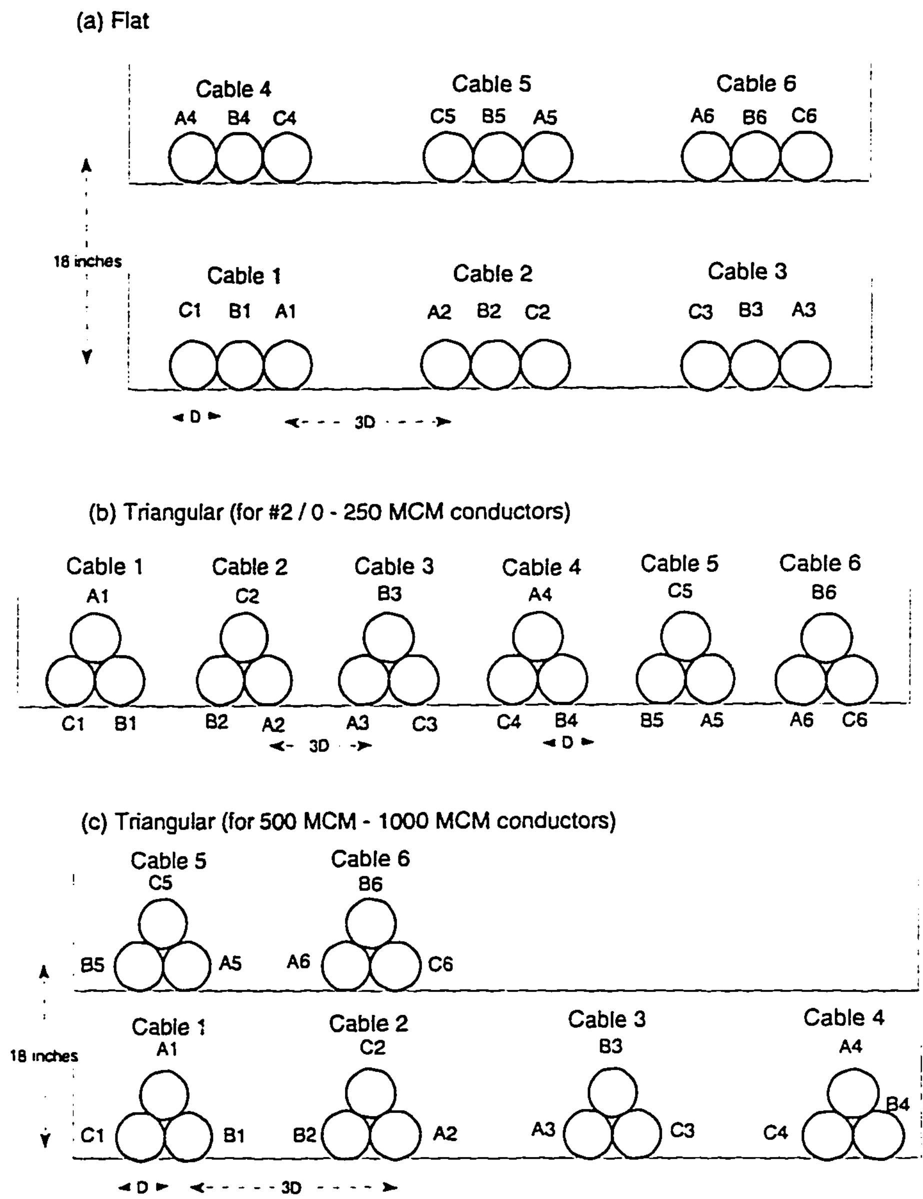


Figure 4.50: A conductor configuration with minimum field of six cables per phase (Three Phase Cable)

Table 4.15: Maximum Value of Magnetic Field obtained for five cables per phase(Three Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration Flat (mG)	Triangular (mG)
1.07	87.50	1.537	1.897
1.20	115.0	2.287	2.727
1.31	127.5	2.791	3.224
1.55	190.0	5.015	6.519
1.78	237.5	7.33	9.413
1.89	272.5	9.009	11.487

Table 4.16: Maximum Value of Magnetic Field obtained for six cables per phase(Three Phase Cables)

Cable Diameter (inch)	Derated Current (A)	Cable Configuration Flat (mG)	Triangular (mG)
1.07	87.50	0.744	0.796
1.20	115.0	1.082	1.293
1.31	127.5	1.294	1.681
1.55	190.0	2.21	2.035
1.78	237.5	3.059	2.961
1.89	272.5	3.656	3.62

4.2 Effect Of Depth on Magnetic Field

As we have seen in the previous section that minimum field values are obtained when the phase locations are as per shown in the drawings. Though the field for the flat and the stack are not very high but still they can be reduced further by increasing the distance between the source and the object. In the previous section the depth of the uppermost conductor was taken as 3 feet and simulated was performed. Here we will implement this technique of magnetic field management by taking three different depths, namely, 3ft, 4ft, and 5ft. The simulation is performed for #4/0 cable size for which the cable diameter is 1.20 inch and the rated current is 230.0 amperes. A 50% derating factor is applied for all the cases.

4.2.1 Single phase cables

The calculated results for the two cable per phase is shown in Table 4.17. Though the field due to the stack and the flat layout are small at a depth of 3ft. still there can be 25 - 35% reduction in case of the stack, flat and the triangular configuration when the depth is increased from 3ft. to 4ft. If the depth is increased by 2 ft. the reduction becomes 42% for triangular and 56% for stack and the flat. In the case of a three cables per phase the minimal field calculated are not very small and the next line of reduction can be to increase the depth beyond 3ft. The reduction obtained are approximately 25% and 40 - 47% for increase of depth by 1ft. and 2ft. respectively for all the three type of conductor arrangement. The results are tabulated in Table 4.18.

In the case of four and six cables per phase with the minimal phase location the field for flat and the stack are small and as such does not really warrant increase in depth. The triangular configuration generates high field and as such needs more attention here. There is appreciable reduction in the field levels ranging from 25-

37% for 1ft. increase in depth and between 38-54% for 2ft. increase in depth for four, five and six cable per phase for all types of configurations. Though, there is appreciable amount of reduction in the maximum field levels one has to pay extra cost in digging. So, actually there is a trade-off between the cost and the amount of reduction one needs. The results are tabulated in Tables 4.19 to 4.21.

Though the results obtained are for a 1.20 inch diameter cable, the reduction pattern holds good even for any different size of the cable if the depth of burial is increased.

The plots of maximum magnetic field values at depths of 3ft, 4ft and 5ft for stack, triangular and flat configurations (five cables per phase case) and cable size of #4/0 are shown in Figs.4.51 to 4.53.

Table 4.17: Effect of Depth for two cables per phase(Single Phase Cables)

Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration Stack (mG)	Triangular (mG)	Flat (mG)
36	1.20	115.0	0.402	6.509	1.484
48	1.20	115.0	0.26	4.862	0.995
60	1.20	115.0	0.177	3.769	0.65

Table 4.18: Effect of Depth for three cables per phase(Single Phase Cables)

Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration Stack (mG)	Triangular (mG)	Flat (mG)
36	1.20	115.0	6.586	9.644	6.137
48	1.20	115.0	4.909	7.217	4.659
60	1.20	115.0	3.799	5.602	3.648

Table 4.19: Effect of Depth for four cables per phase(Single Phase Cables)

Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration Stack (mG)	Triangular (mG)	Flat (mG)
36	1.20	115.0	0.475	9.541	0.783
48	1.20	115.0	0.305	7.392	0.471
60	1.20	115.0	0.208	5.897	0.303

Table 4.20: Effect of Depth for five cables per phase(Single Phase Cables)

Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration Stack (mG)	Triangular (mG)	Flat (mG)
36	1.20	115.0	6.593	12.793	4.725
48	1.20	115.0	4.912	9.818	3.609
60	1.20	115.0	3.801	7.777	2.857

Table 4.21: Effect of Depth for six cables per phase(Single Phase Cables)

Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration Stack (mG)	Triangular (mG)	Flat (mG)
36	1.20	115.0	1.49	15.977	2.024
48	1.20	115.0	0.965	12.207	1.395
60	1.20	115.0	0.66	9.634	0.999

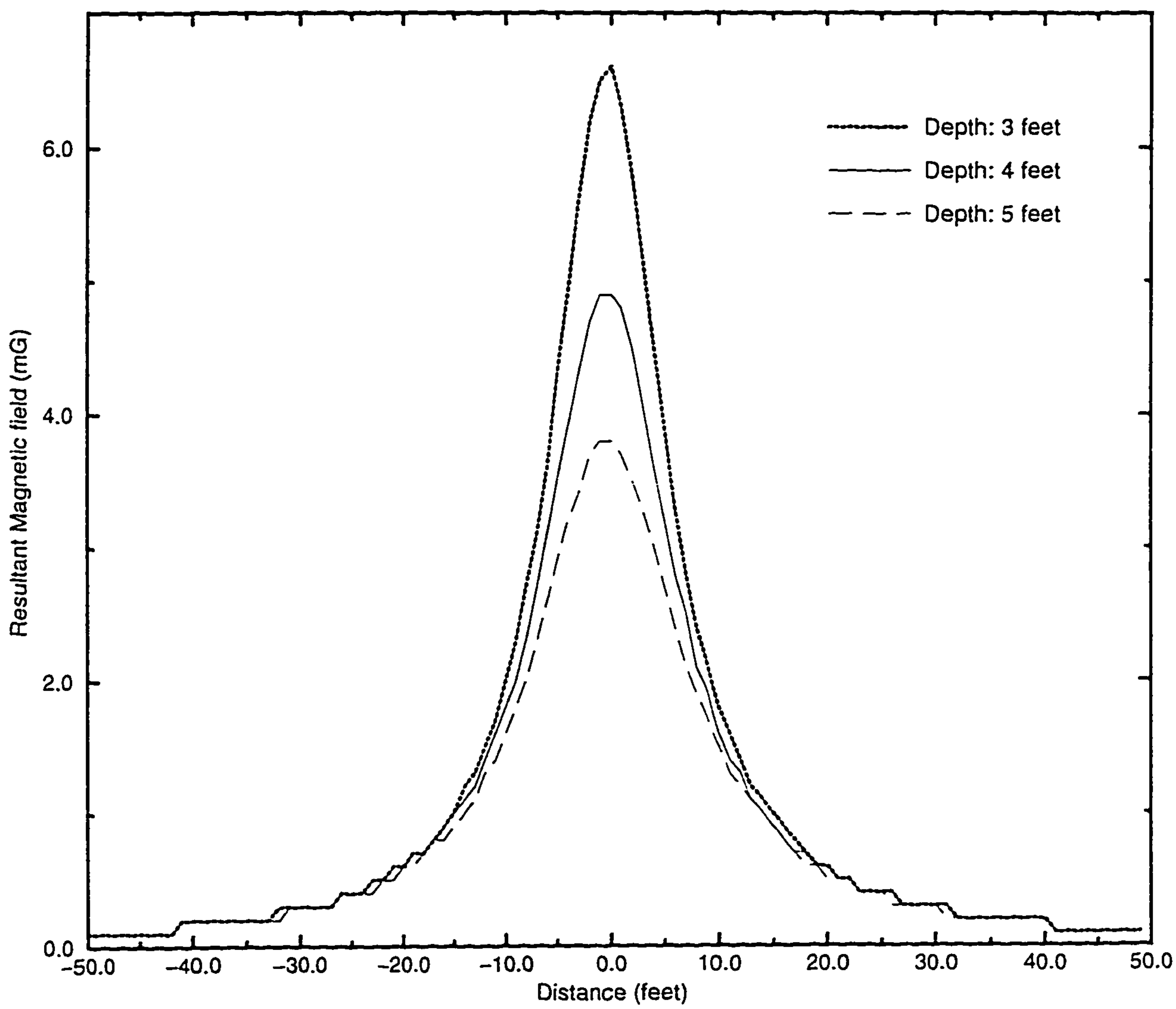


Figure 4.51: Effect of Depth for Stack Configuration, Five Cables per Phase, Cable dia. 1.20 inch (Single Phase Cable)

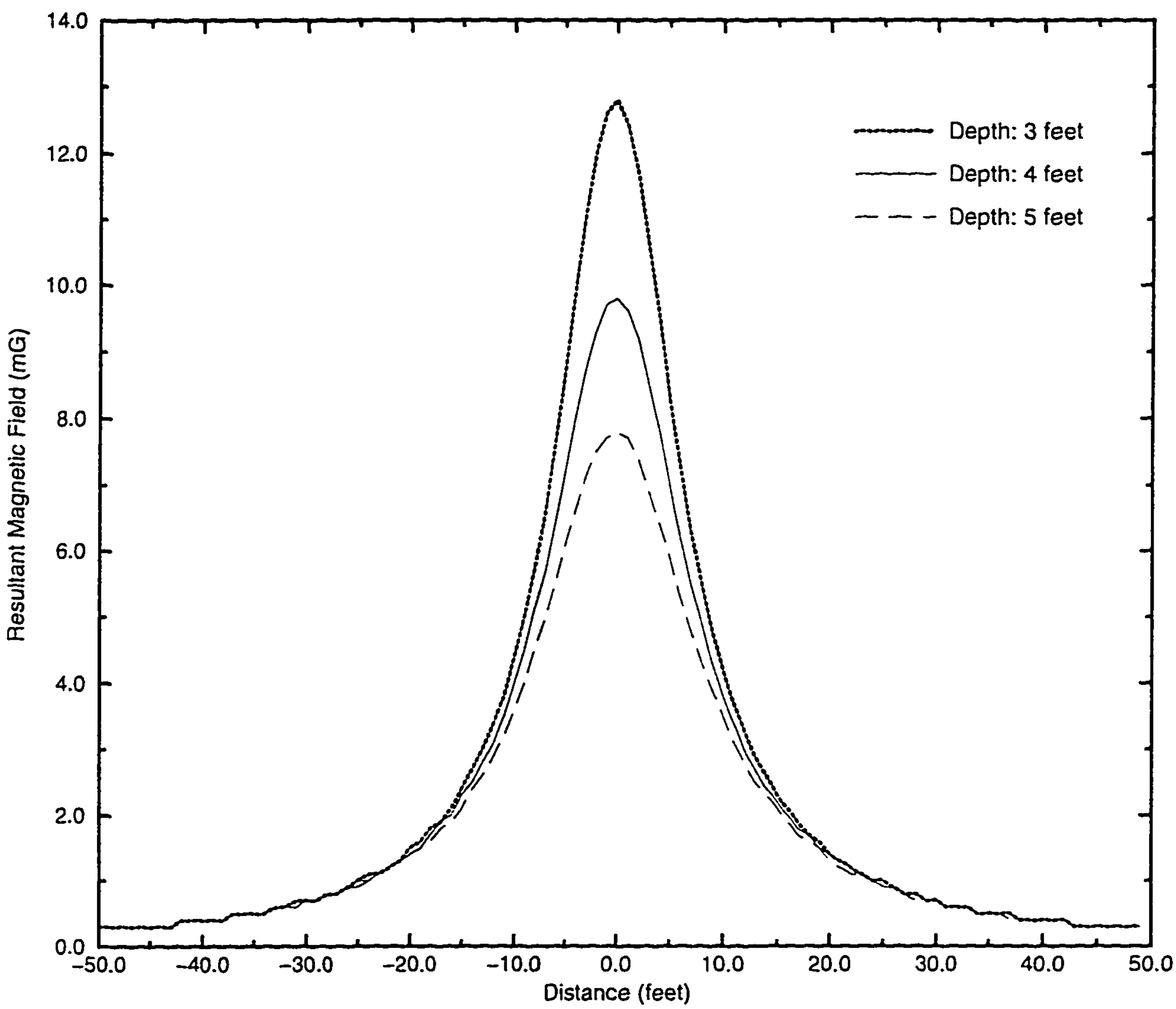


Figure 4.52: Effect of Depth for Triangular Configuration. Five Cables per Phase, Cable dia. 1.20 inch (Single Phase Cable)

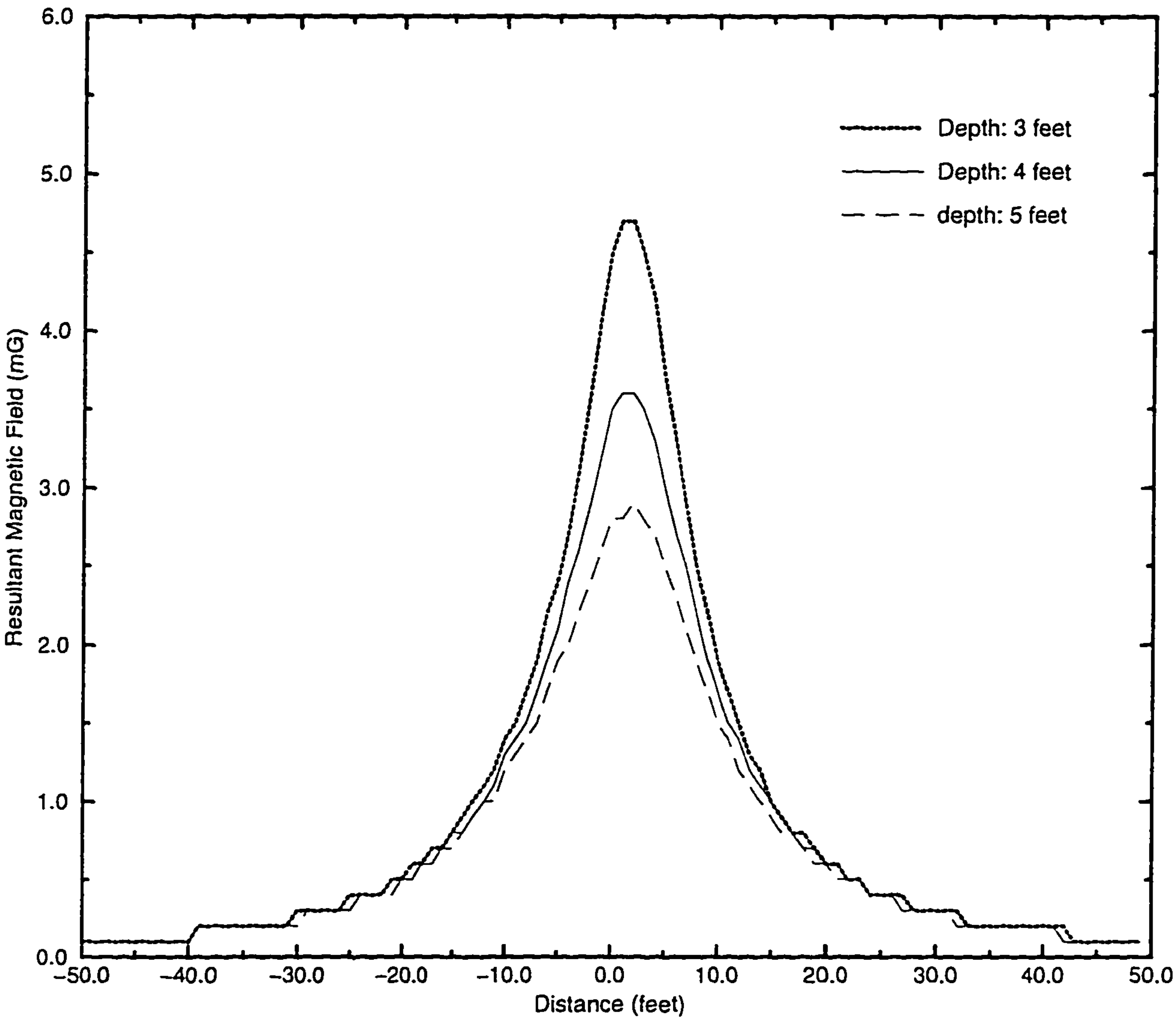


Figure 4.53: Effect of Depth for Flat Configuration, Five Cables per Phase, Cable dia. 1.20 inch (Single Phase Cable)

4.2.2 Three phase cables

In the case of three cable two type of configuration the flat and the triangular are considered for #4/0 size cable. Again the parameters are fixed as the same as the one for a single phase cable. For a two cables per phase, the results obtained by simulation are given in Table 4.22. As seen from the table for 3ft. depth the field is 0.529 and 6.447 mG for the flat and triangular configurations respectively. Now, when the depth is increased by 1ft. and 2ft. the field as expected is getting reduced, the percentage of reduction being in the range of 25 to 36% for 4ft. depth and 42 to 56% for 5ft. depth.

Similarly, for a three cables per phase cable from a 9.625 mG field value it comes down to 5.588 mG by just increasing the depth by 2ft.(refer Table 4.23) for a triangular configuration. The field for a flat configuration is maximum for three cables per phase having a value of 3.188 mG for 3ft. depth. The reason being the conductor layout for such a case (refer Fig.4.47). The two trays are separated by 18 inches and as such due to increased distance between the source and the object the field levels are lower. It can be brought down to a level of 2.396 mG and further down to 1.864 mG by successively increasing the depths by 1ft. For a four, five and six cables per phase (flat configuration) the field is already low and does not warrant reduction. The values due to triangular are high and requires more attention. The reduction due to 1ft. increase in depth for delta configuration is 25 % for the four, five and six cables per phase. The results are tabulated in Tables 4.24 to 4.26.

The plots of maximum magnetic field values at depths of 3ft, 4ft and 5ft for flat and triangular configurations (five cables per phase case) and cable size of #4/0 are shown in Figs.4.54 and 4.55.

Table 4.22: Effect of Depth for two cables per phase(Three Phase Cables)

0Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration	
			Flat (mG)	Triangular (mG)
36	1.20	115.0	0.529	6.447
48	1.20	115.0	0.34	4.818
60	1.20	115.0	0.231	3.736

Table 4.23: Effect of Depth for three cables per phase(Three Phase Cables)

Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration	
			Flat (mG)	Triangular (mG)
36	1.20	115.0	3.188	9.625
48	1.20	115.0	2.396	7.201
60	1.20	115.0	1.864	5.588

Table 4.24: Effect of Depth for four cables per phase(Three Phase Cables)

Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration	
			Flat (mG)	Triangular (mG)
36	1.20	115.0	1.258	12.745
48	1.20	115.0	0.839	9.552
60	1.20	115.0	0.587	7.422

Table 4.25: Effect of Depth for five cables per phase(Three Phase Cables)

Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration Flat (mG)	Triangular (mG)
36	1.20	115.0	2.287	15.793
48	1.20	115.0	1.761	11.862
60	1.20	115.0	1.403	9.23

Table 4.26: Effect of Depth for six cables per phase(Three Phase Cables)

Cable Depth (inch)	Cable Diameter (inch)	Derated Current (A)	Cable Configuration Flat (mG)	Triangular (mG)
36	1.20	115.0	1.082	18.751
48	1.20	115.0	0.734	14.122
60	1.20	115.0	0.52	11.007

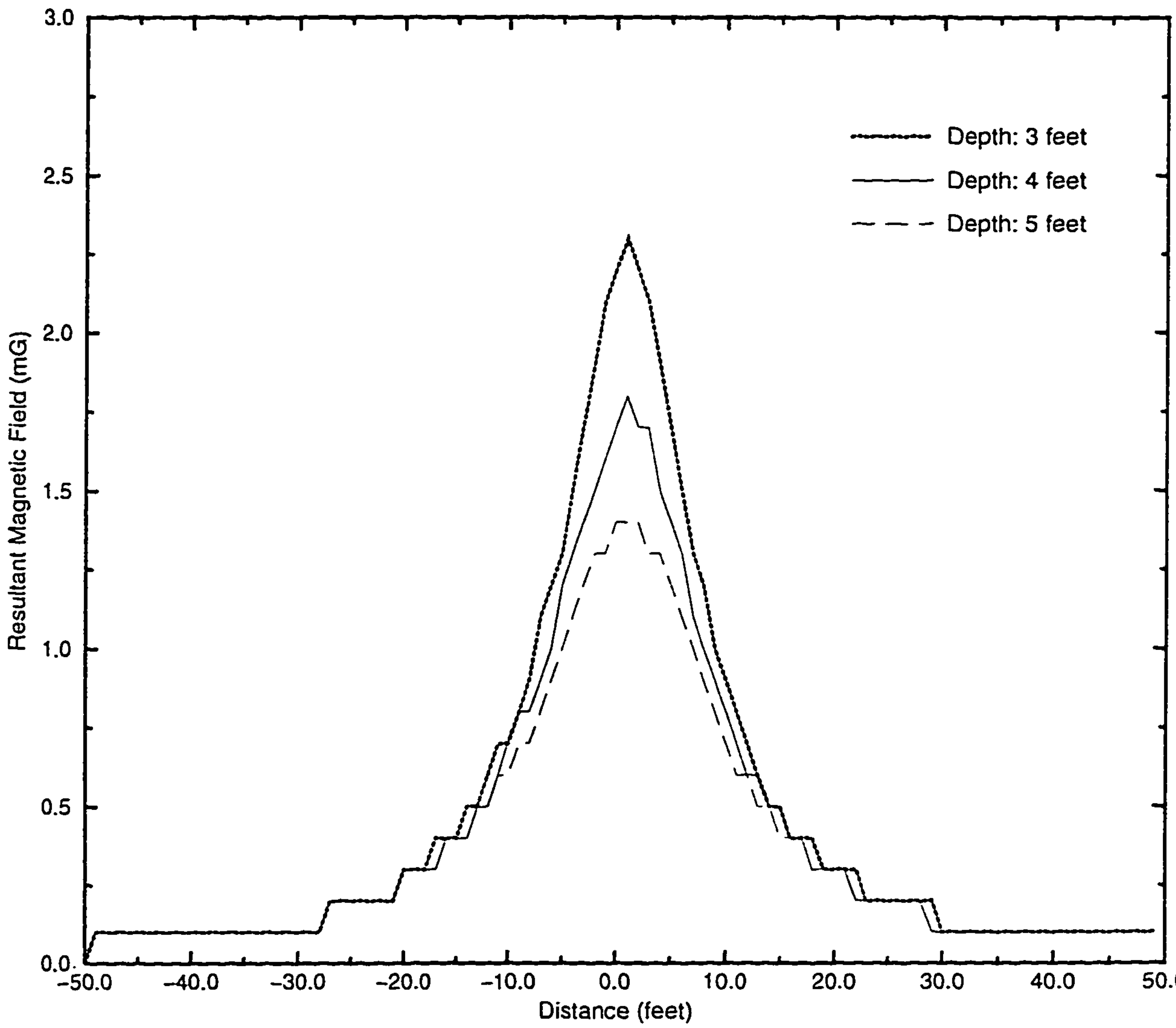


Figure 4.54: Effect of Depth for Flat Configuration, Five Cables per Phase, Cable dia. 1.20 inch (Three Phase Cable)

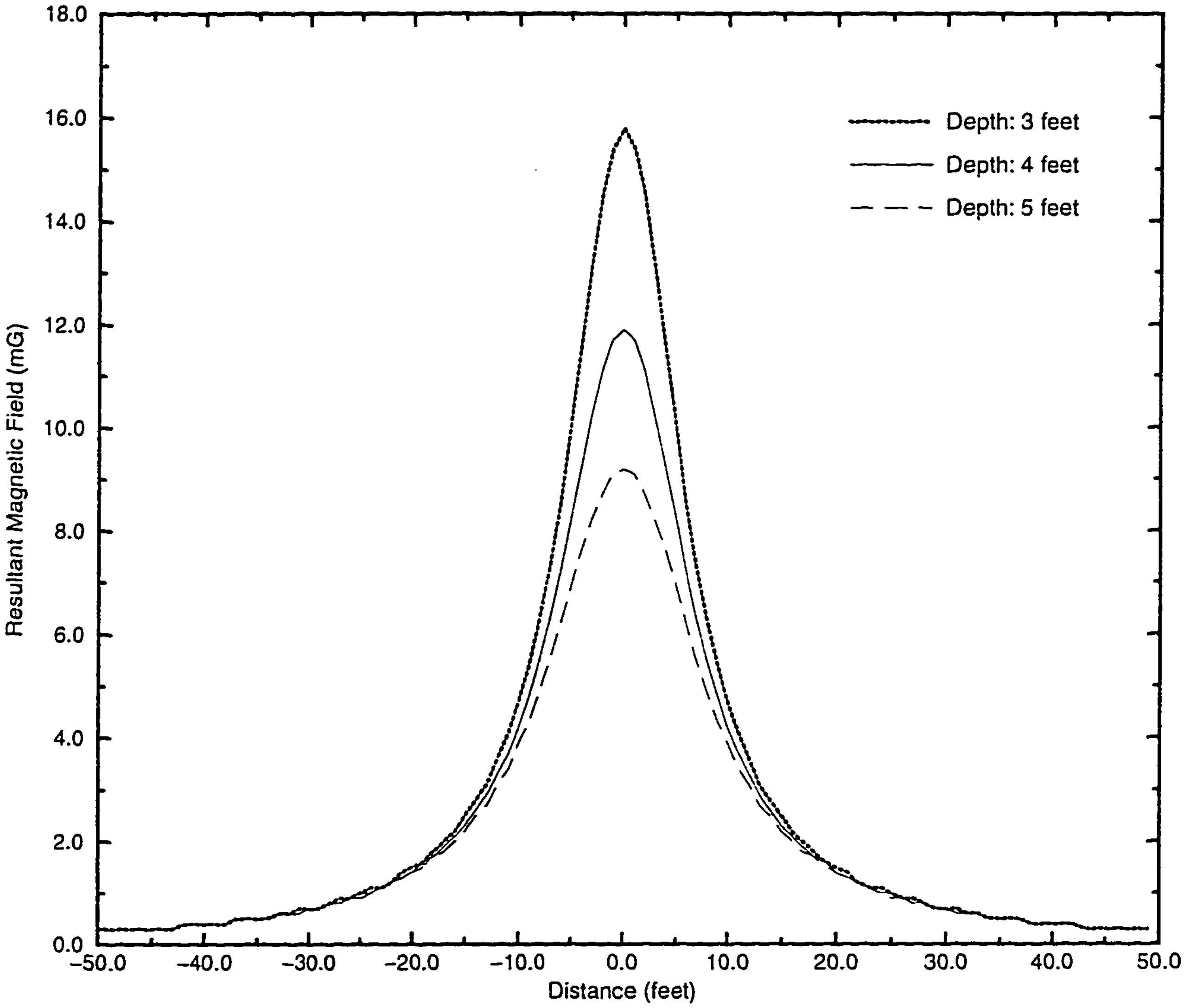


Figure 4.55: Effect of Depth for Triangular Configuration (Three Phase Cable)

4.3 Simulation of the Proposed New Design

Some of the new designs for conductor configuration are being proposed in this thesis work. The designs proposed are for a single circuit, double circuit, three cables per phase, and four cables per phase. All these designs are studied from the magnetic field perspective and other advantges and for each type of circuit a particular phase arrangement is recommended which gives the minimum field.

4.3.1 Single circuit line

For a single circuit line the design being proposed is shown in Fig.4.56. The simulated value for magnetic field at a depth of 3 ft. for a flat arrangement having a cable dia. of 1.20 inch is 6.62 mG. For the design proposed which is basically a right angle triangle arrangement the simulated value of field at the same depth and same cable size is found to be 4.54 mG. Hence there is significant reduction as compared to the flat arrangement.

4.3.2 Double circuit line

For a double circuit line the conductor arrangement which is being proposed is shown in Fig.4.57. All possible location of the three phases a, b,and c are tried. There will be 36 possible combinations. The conductors are arranged in right angle triangle fashion. The simulated values for a 1.20 inch dia. cable are tabulated in Table 4.27. The maximum field is obtained when the left half is a mirror of the right half, the field value being 7.652mG. The least field is when the left half is the inverted image of the right half. Here maximum field cancellation occurs and its value is 4.281mG. Hence, this particular configuration is proposed. The best and the worst case plot is shown in Fig. . Other intermediate cases are plotted and shown in Figs. 4.59 and 4.60. Though the new design simulated cases does not reduce the values in

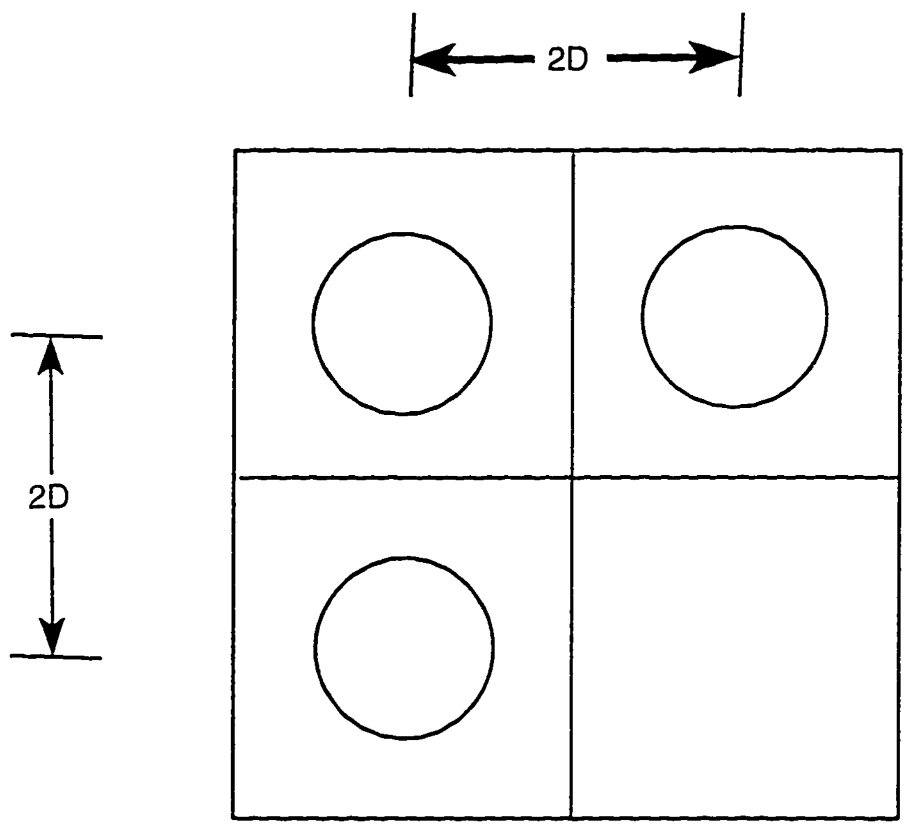


Figure 4.56: New Design - Single Circuit(3 conductors)

comparison to the standard configurations but the symmetry in the geometry gives a position in the layout where the neutral conductor can be placed very conveniently. The phase locations shown in Fig.4.57 corresponds to the minimum field.

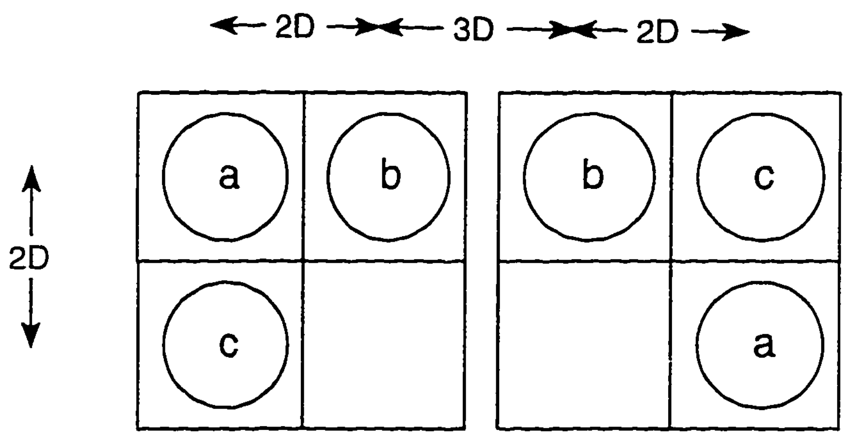


Figure 4.57: New Design - Double Circuit(6 conductors)

Table 4.27: Max. magnetic field values (mG) for double circuit (New Design, Cable dia. 1.20 inch)

a b a b c c (7.652)	a b a c c b (7.177)	a b c a c b (5.893)	a b c b c a (7.177)	a b b c c a (4.281)	a b b a c c (7.67)
a c a b b c (7.177)	a c a c b b (7.652)	a c c a b b (7.67)	a c c b b a (4.281)	a c b c b a (7.177)	a c b a b c (5.893)
c a a b b c (4.281)	c a a c b b (7.67)	c a c a b b (7.652)	c a c b b a (7.177)	c a b c b a (5.893)	c a b a b c (7.177)
c b a b a c (7.177)	c b a c a b (5.893)	c b c a a b (7.177)	c b c b a a (7.652)	c b b c a a (7.67)	c b b a a c (4.281)
b c a b a c (5.893)	b c a c a b (7.177)	b c c a a b (4.281)	b c c b a a (7.67)	b c b c a a (7.652)	b c b a a c (7.177)
b a a b c c (7.67)	b a a c c b (4.281)	b a c a c b (7.177)	b a c b c a (5.893)	b a b c c a (7.177)	b a b a c c (7.652)

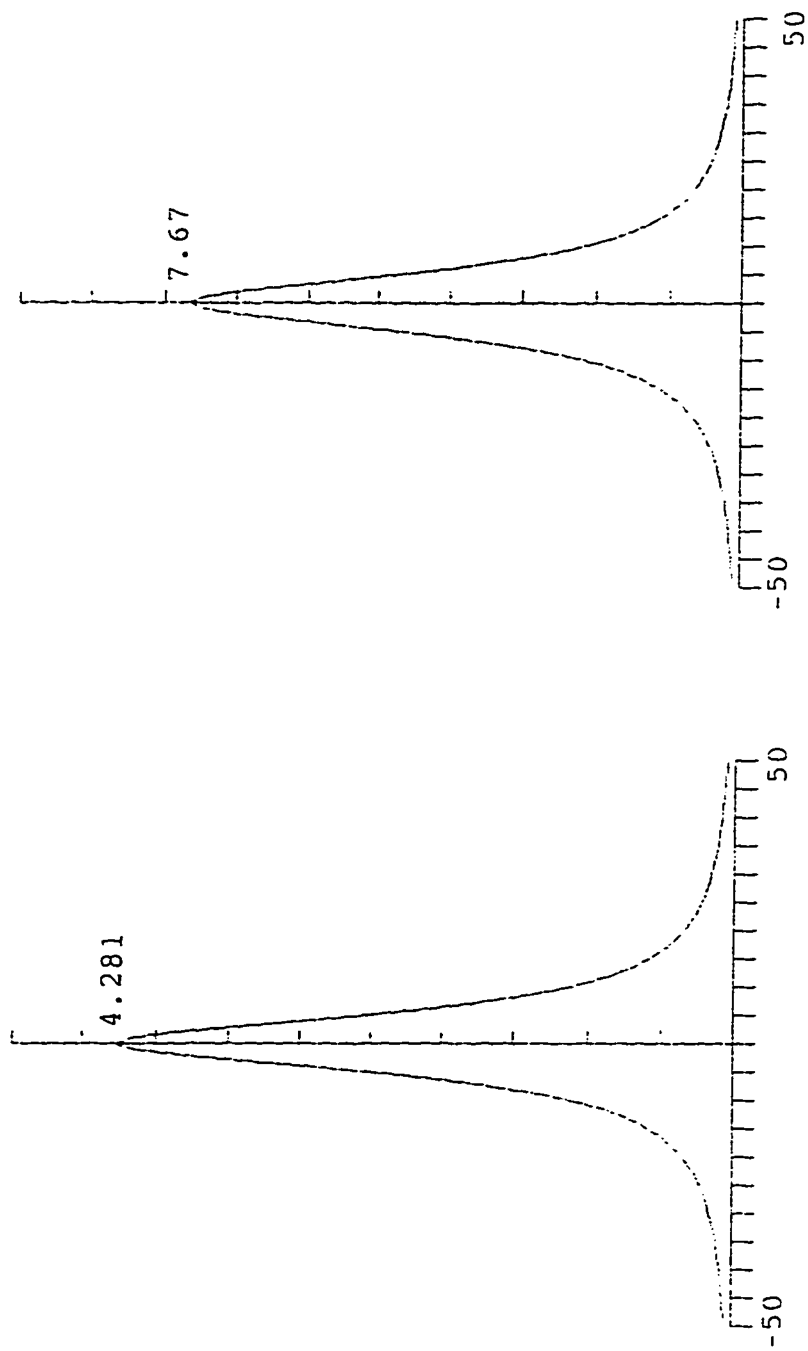


Figure 4.58: Plot for New Design, Two Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

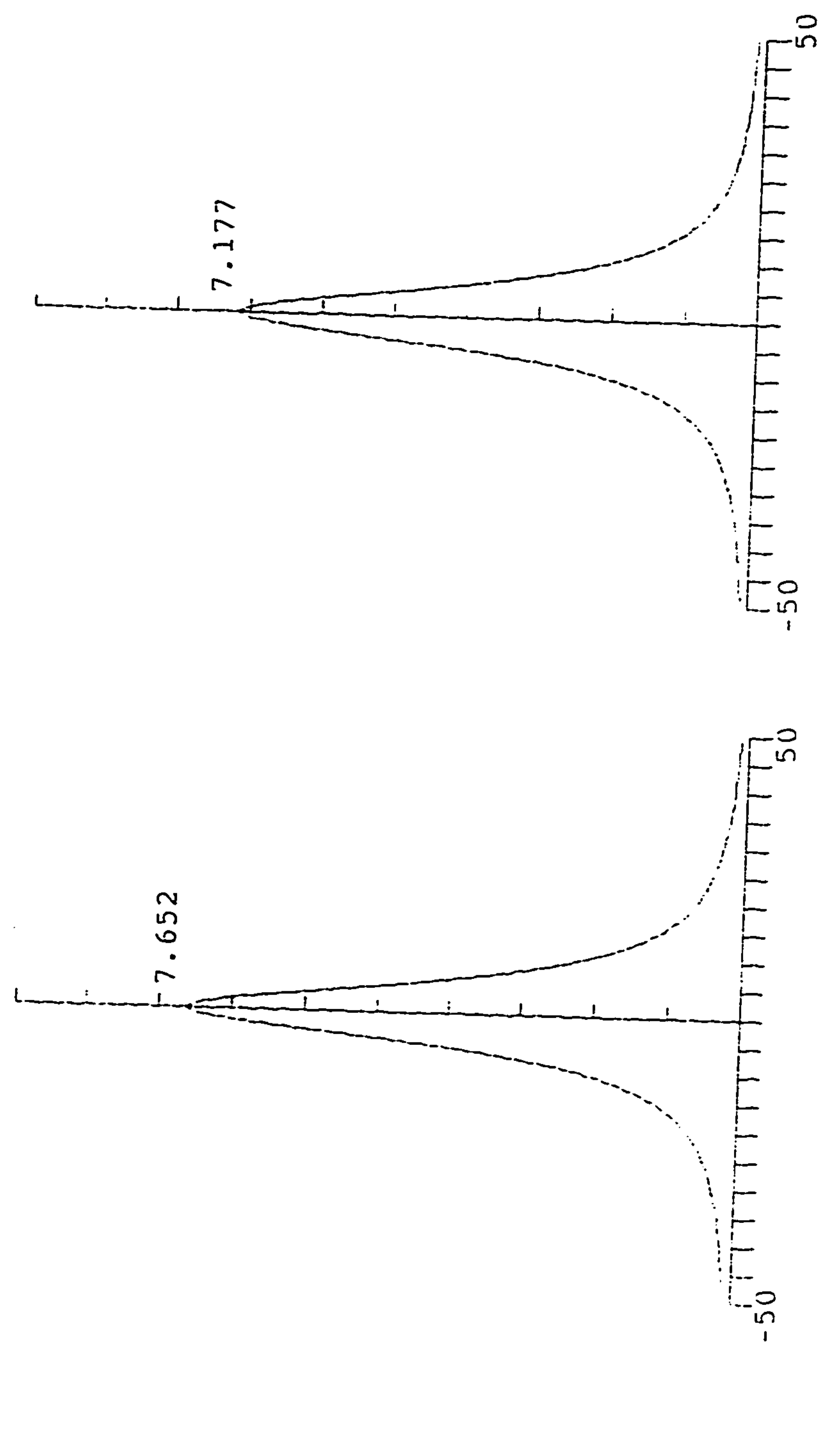


Figure 4.59: Plot for New Design, Two Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

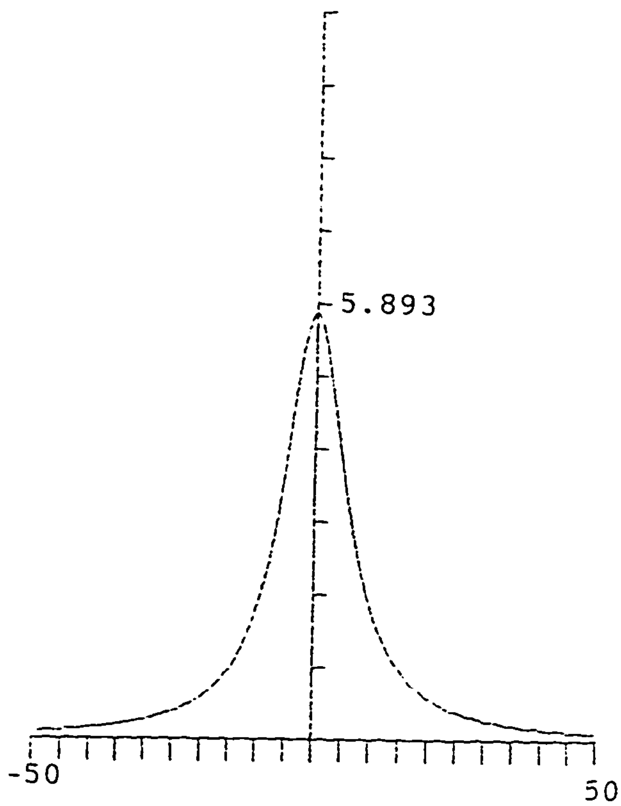


Figure 4.60: Plot for New Design, Two Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

4.3.3 Three cables per phase

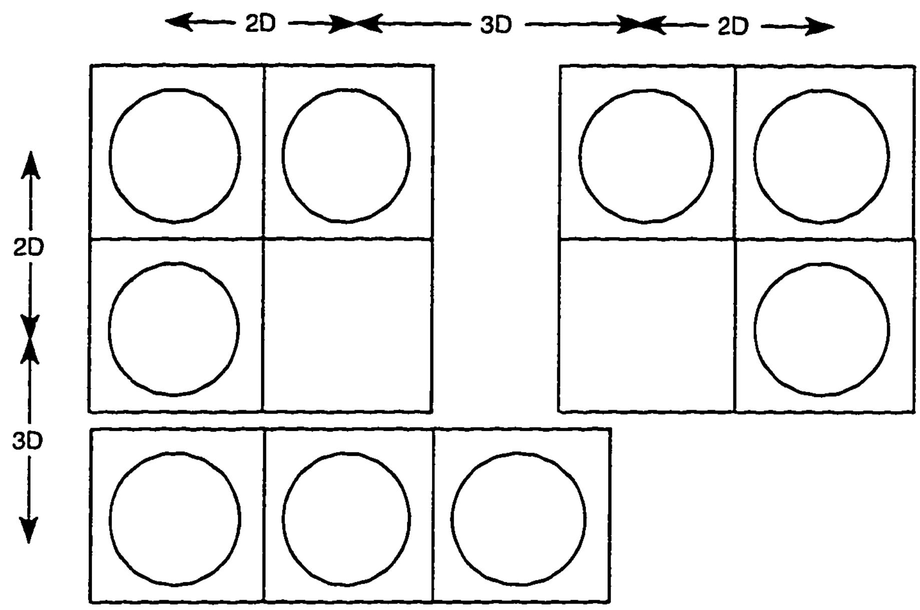
The layout that are proposed for a three cables per phase having 9 conductors are shown in Fig.4.61. The two upper sets that are arranged in right angle triangle fashion can are symmetrical with each other and the image and the inverted image phase relationships can be used for maximum field cancellation. The other three conductor can be placed in flat arrangement as shown in case (a) or case (b) of the above mentioned figure. The fields are calculated for a 1.20 inch dia. cable.

In Figs.4.62 different cases starting from (1) to (6) shows six different combinations for the three conductors placed in flat fashion. There is no imaging or inverted image relationship between the two sets of right angle triangle. As shown the field ranges from 12.269mG to 7.56mG. The value obtained for the EPRI recommended stack, triangular and the flat configurations for the same currents was simulated and found to be 6.586, 0.822 and 6.137 mG respectively. Hence, the value of 7.56mG for phase configuration shown in Fig.4.62 is more than all the standard configurations.

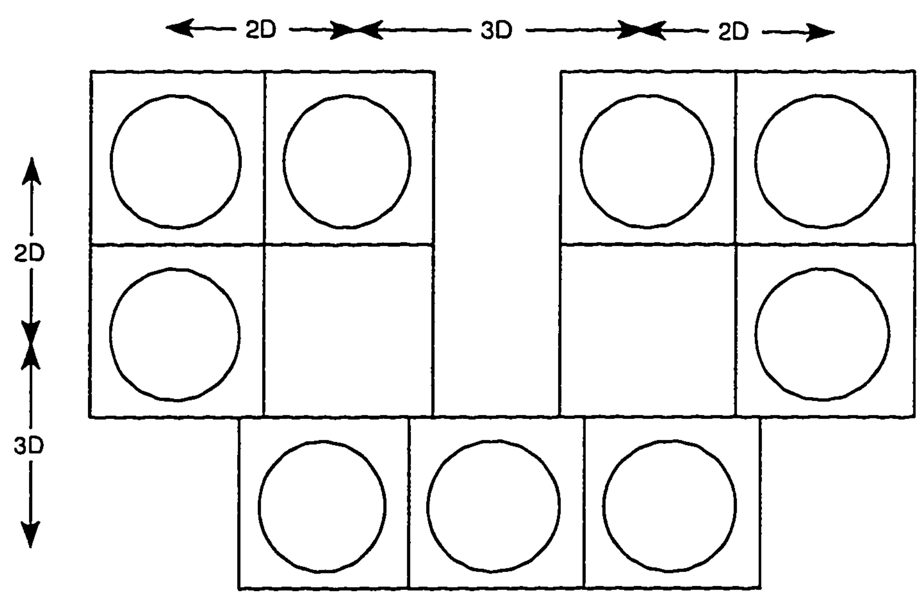
In Fig.4.63 the two triangular sets form an image of each other. Six different combinations for the lower set are again tried but there was not much improvement in the results. The values ranges between 7.567 to 9.535 mG. Next the cancellation of fields when the two symmetrical sets form an inverted image of each other were studied. As shown in Fig.4.64 the field value comes below the lowest value for the EPRI's stack and the flat configurations. The least value obtained is 5.014 mG which is less than the values obtained for the stack and the flat configurations. If we look at the bus arrangement for the least field carefully, it is observed that the upper two sets are inverted image of each other and two phases b and c are below the corresponding positions of the upper set of conductor while phase a have diagonal positions. Obviously, cancellation is maximum in this bus arrangement.The percentage reduction as compared to stack and the flat configurations in the resultant field value is approximately 25% and 18% respectively which is a significant reduction. The plots for all the cases considered for Case (a) are shown in Fig.4.65 to Fig.4.73.

The other possible arrangement for the lower three conductors is shown in Case (b) of Fig.4.61. Here, the lower set of conductors are placed at the centre of the geometry formed. The lowest value obtained here is 4.98 mG which is very near to the minimum obtained for Case (a). Hence, any one of the two designs are equally recommendable. The phase locations along with the simulated values obtained are shown in Figs.4.74 to 4.76 and the plots are shown in Figs.4.77 to 4.78.

Though the total number of combinations generated will be very large it is not necessary to simulate all the possible cases. The logic derived by simulating all the possible phase locations for a double circuit line can be utilized here and only a few selected cases need to be simulated. This new design proposed with the phase locations for minimum field for three cables per phase gives a lesser field as compared to stack and the flat but more in comparison to the triangular but it has advantage of accomodating the neutral conductor in the symmetrical structure.



Case (a)



Case (b)

Figure 4.61: New Designs - Three Cables per Phase

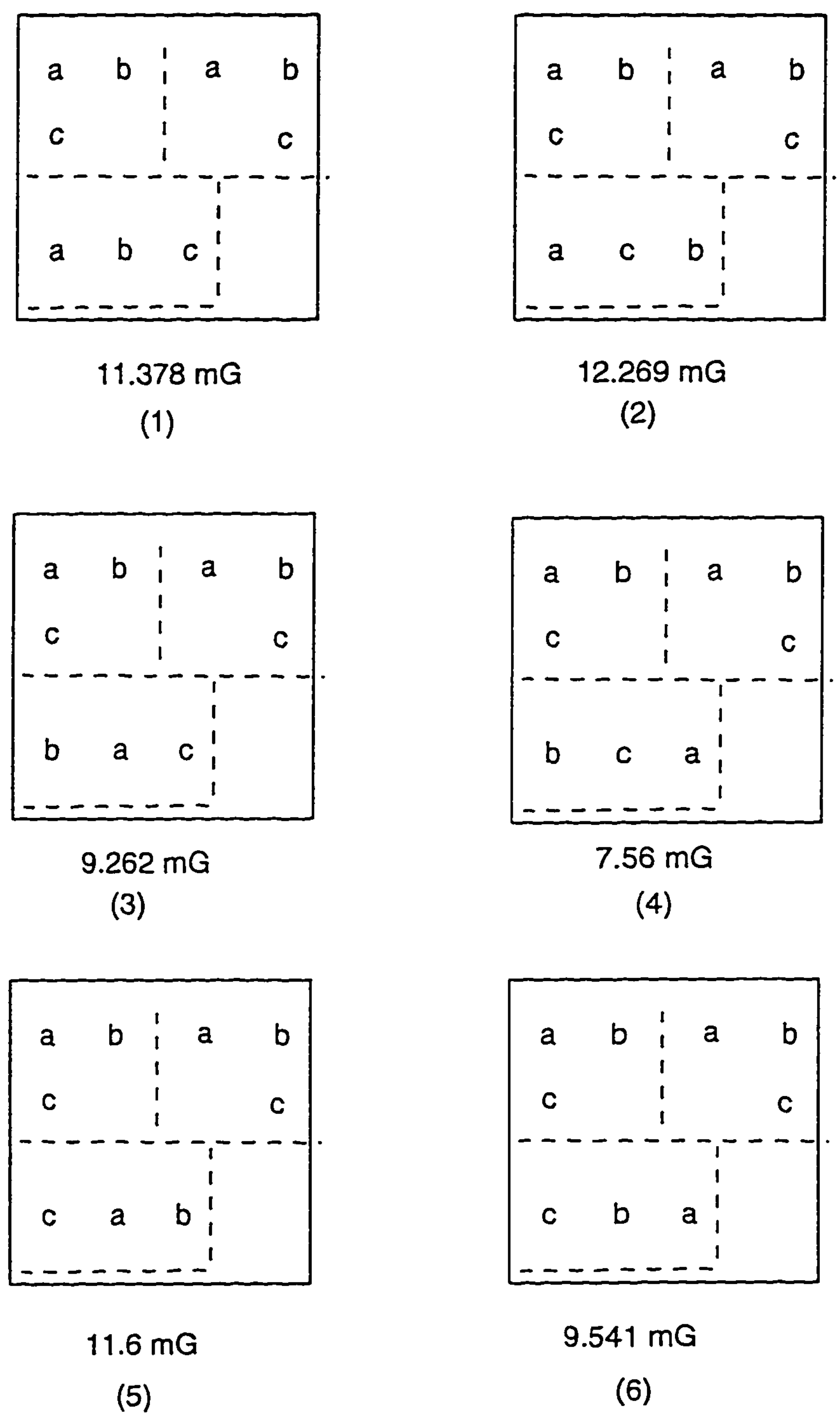


Figure 4.62: New Design Case (a) - Three Cables per Phase (9 conductors)

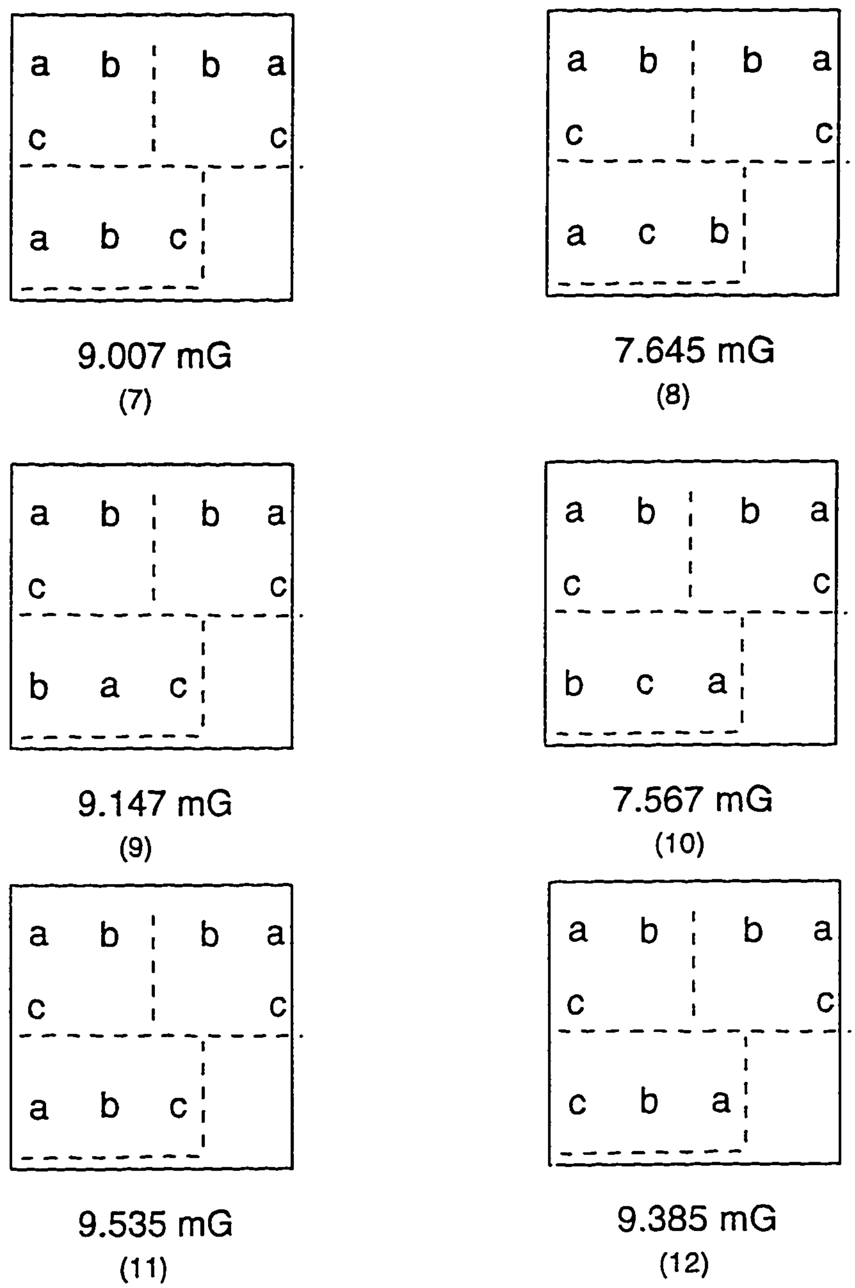


Figure 4.63: New Design Case (a) - Three Cables per Phase (contd.)(9 conductors)

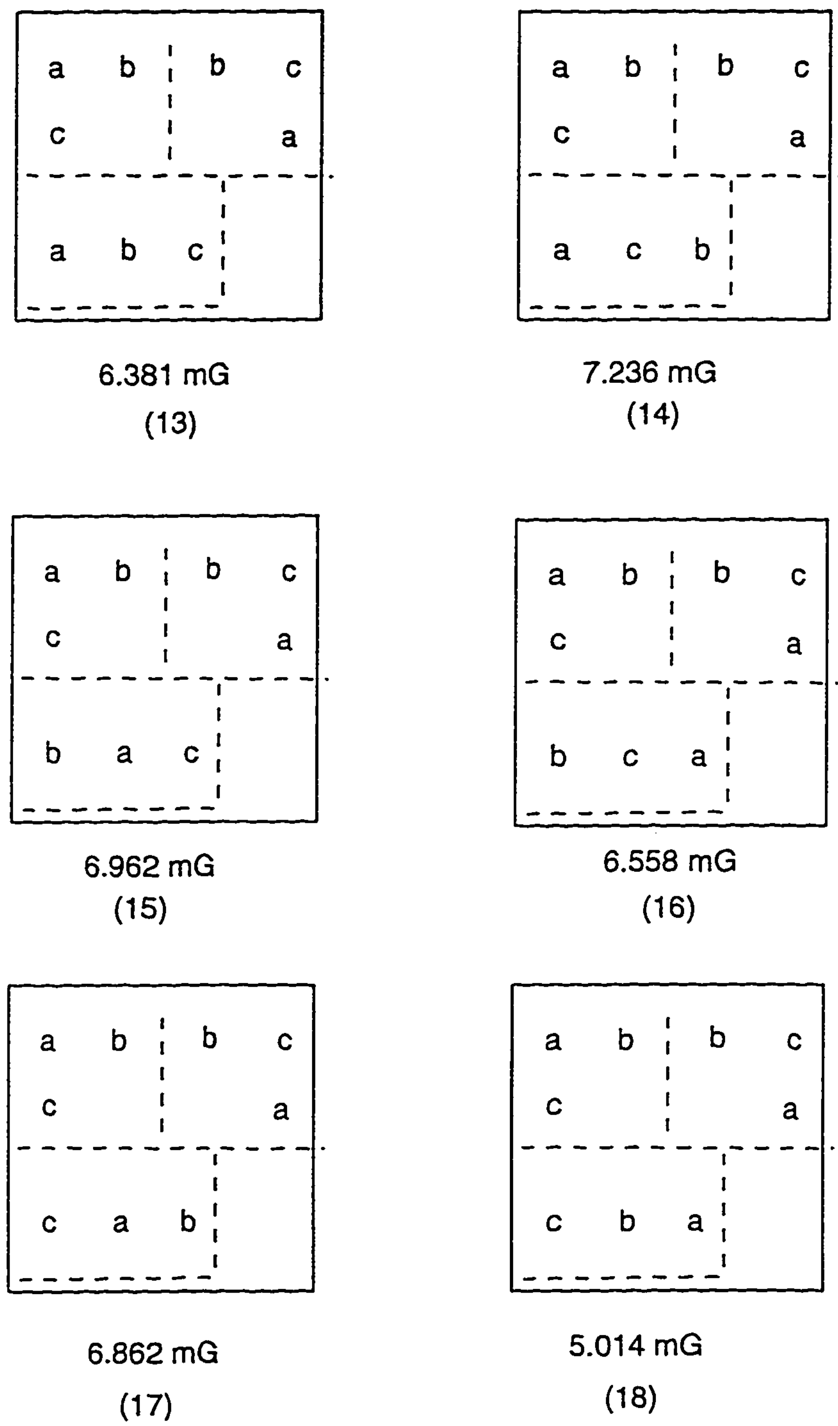


Figure 4.64: New Design Case (a) - Three Cables per Phase (contd.)(9 conductors)

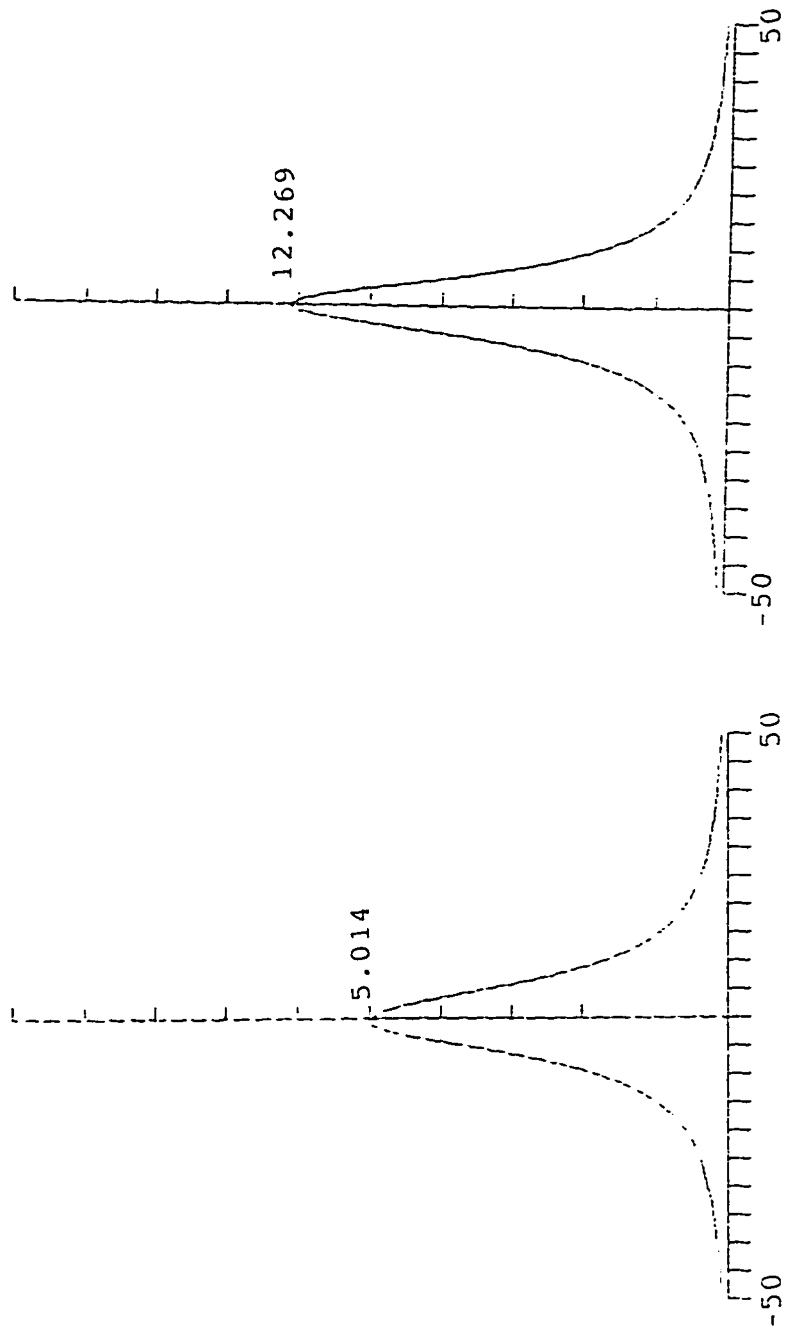


Figure 4.65: Plot for New Design Case (a), Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

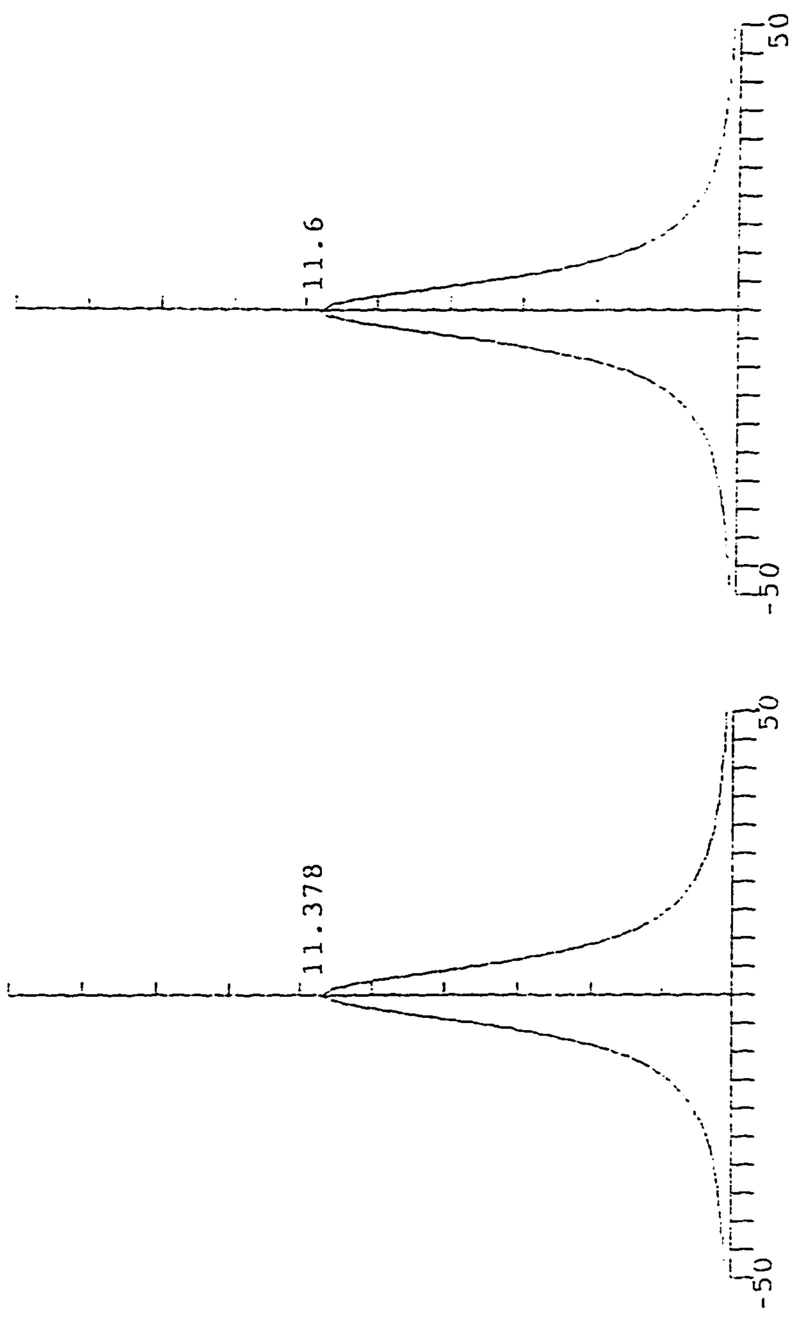


Figure 4.66: Plot for New Design Case (a), Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

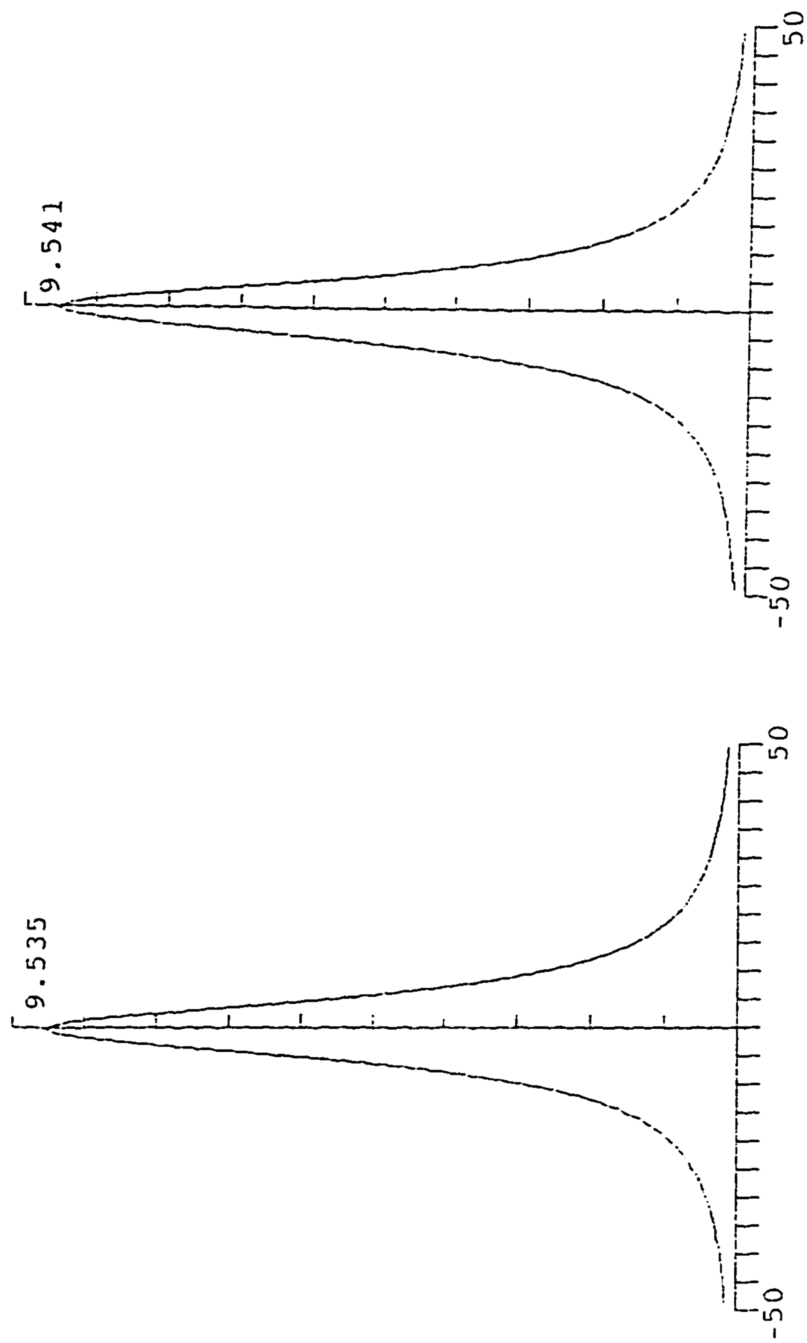


Figure 4.67: Plot for New Design Case (a), Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

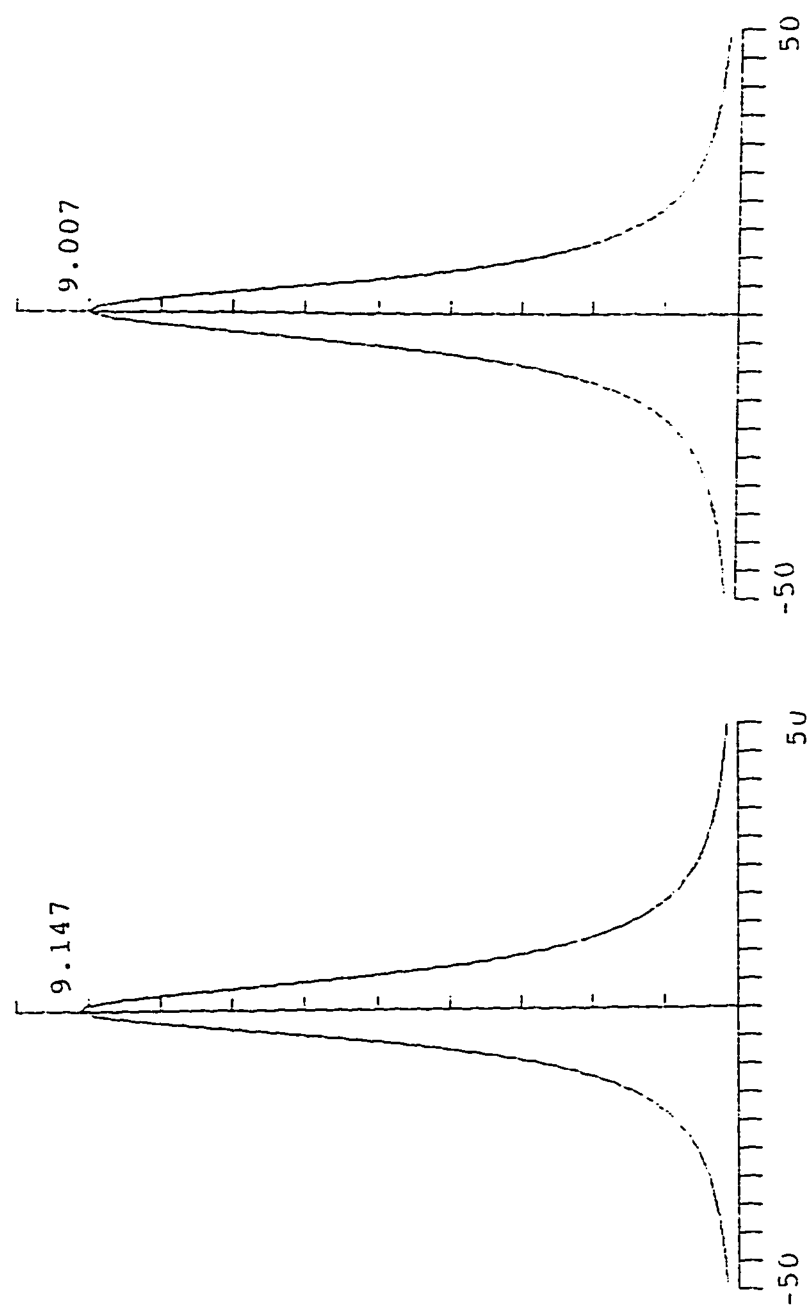


Figure 4.68: Plot for New Design Case (a). Three Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

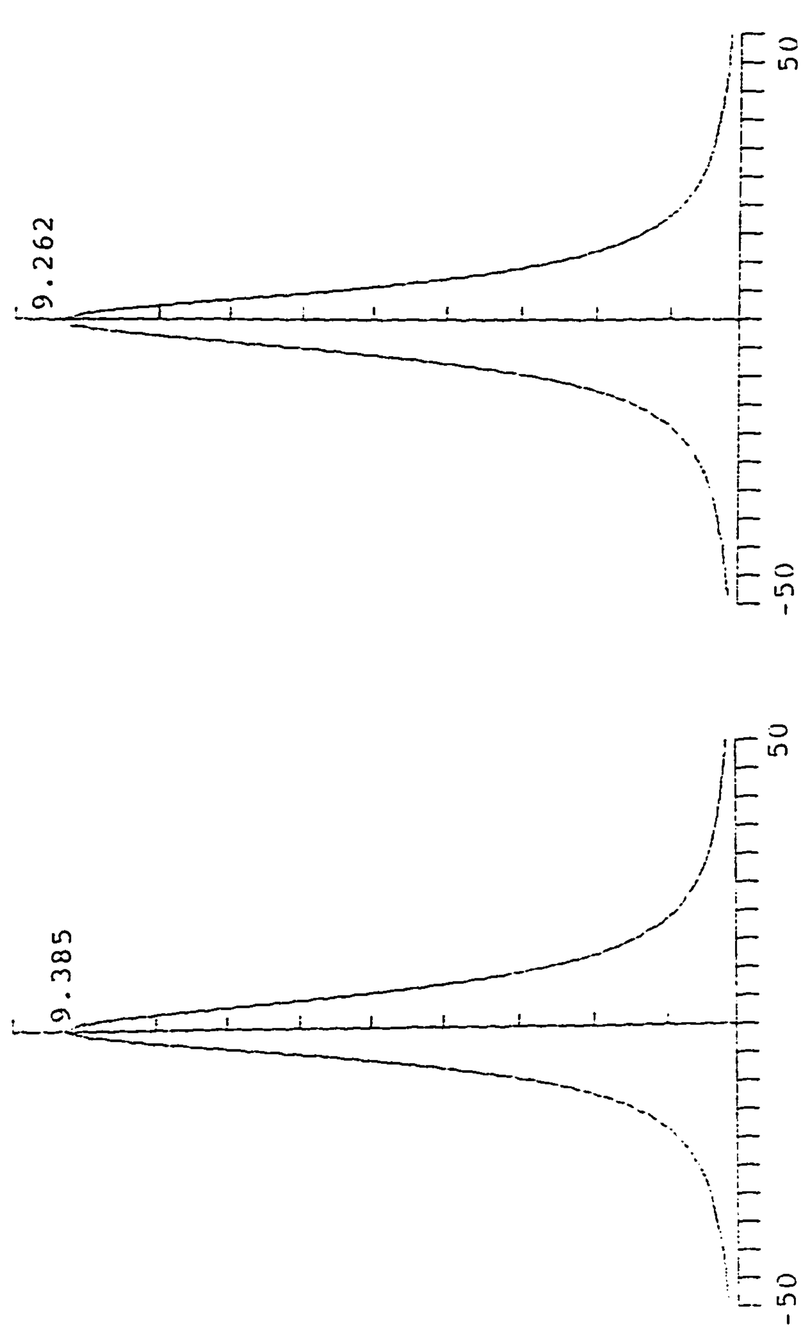


Figure 4.69: Plot for New Design Case (a), Three Cables per phase. Cable dia. 1.20 inch (Single Phase Cable). Intermediate cases

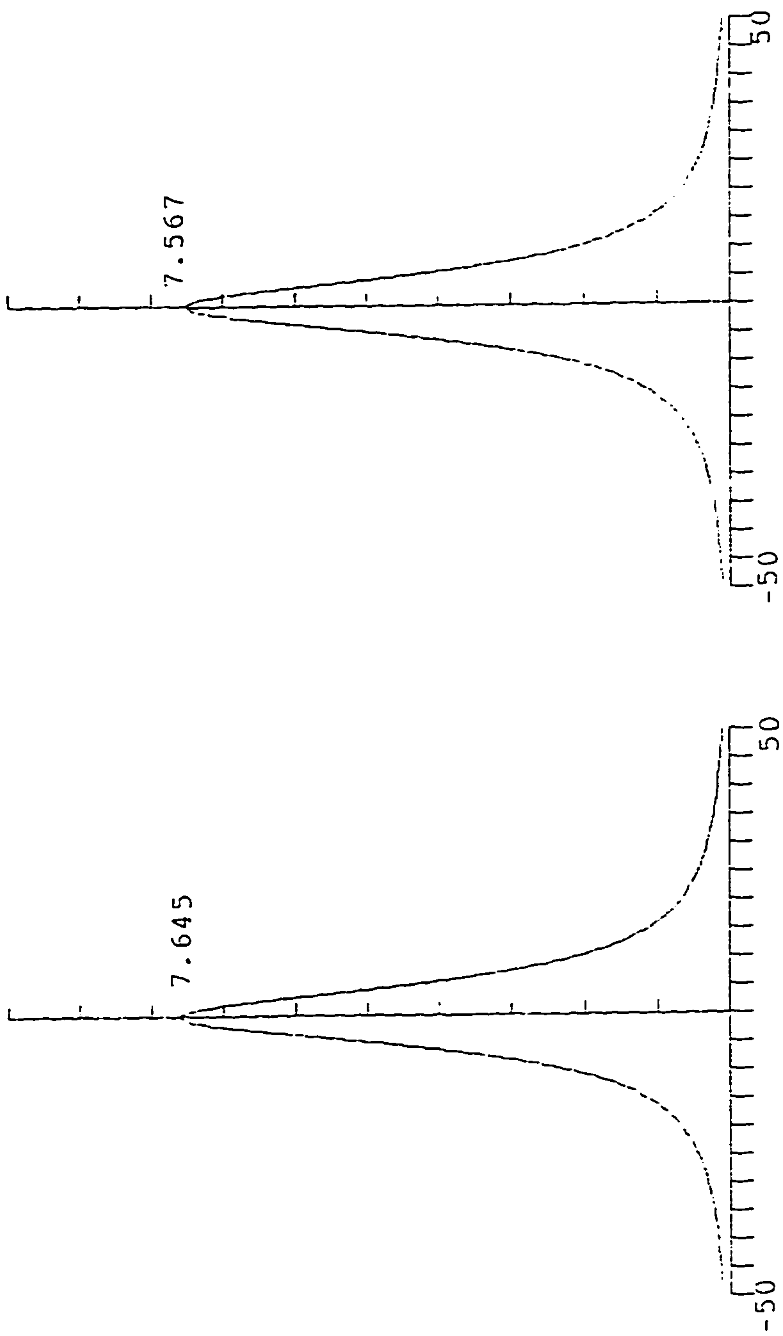


Figure 4.70: Plot for New Design Case (a). Three Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

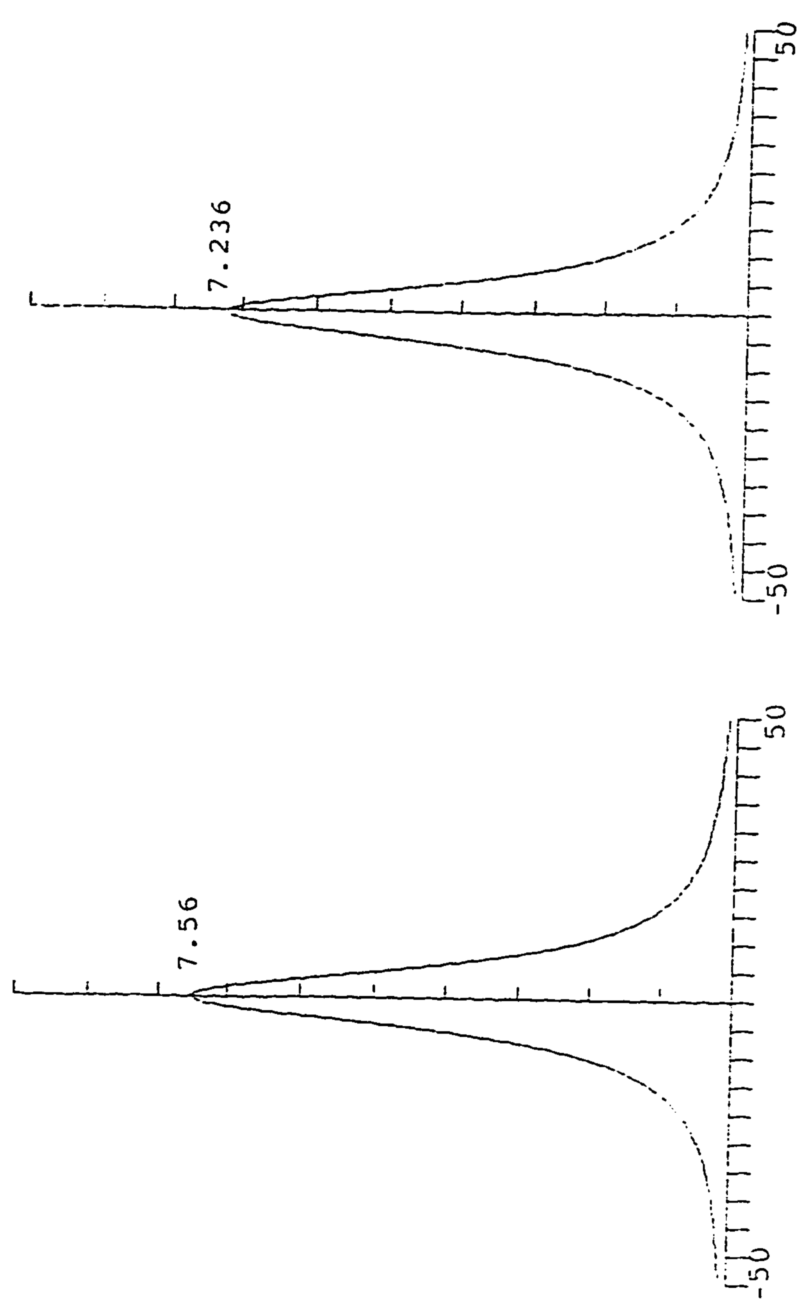


Figure 4.71: Plot for New Design Case (a). Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

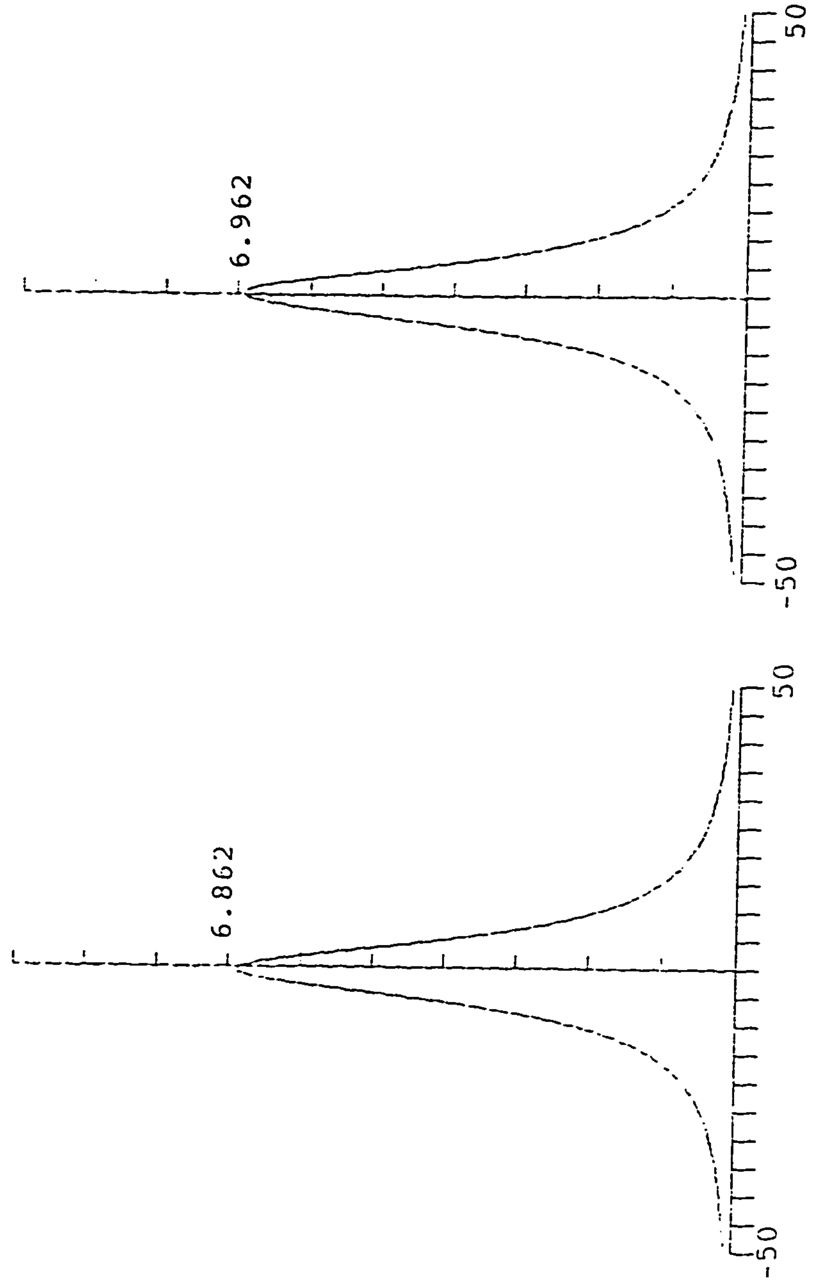


Figure 4.72: Plot for New Design Case (a). Three Cables per phase. Cable dia. 1.20 inch (Single Phase Cable). Intermediate cases

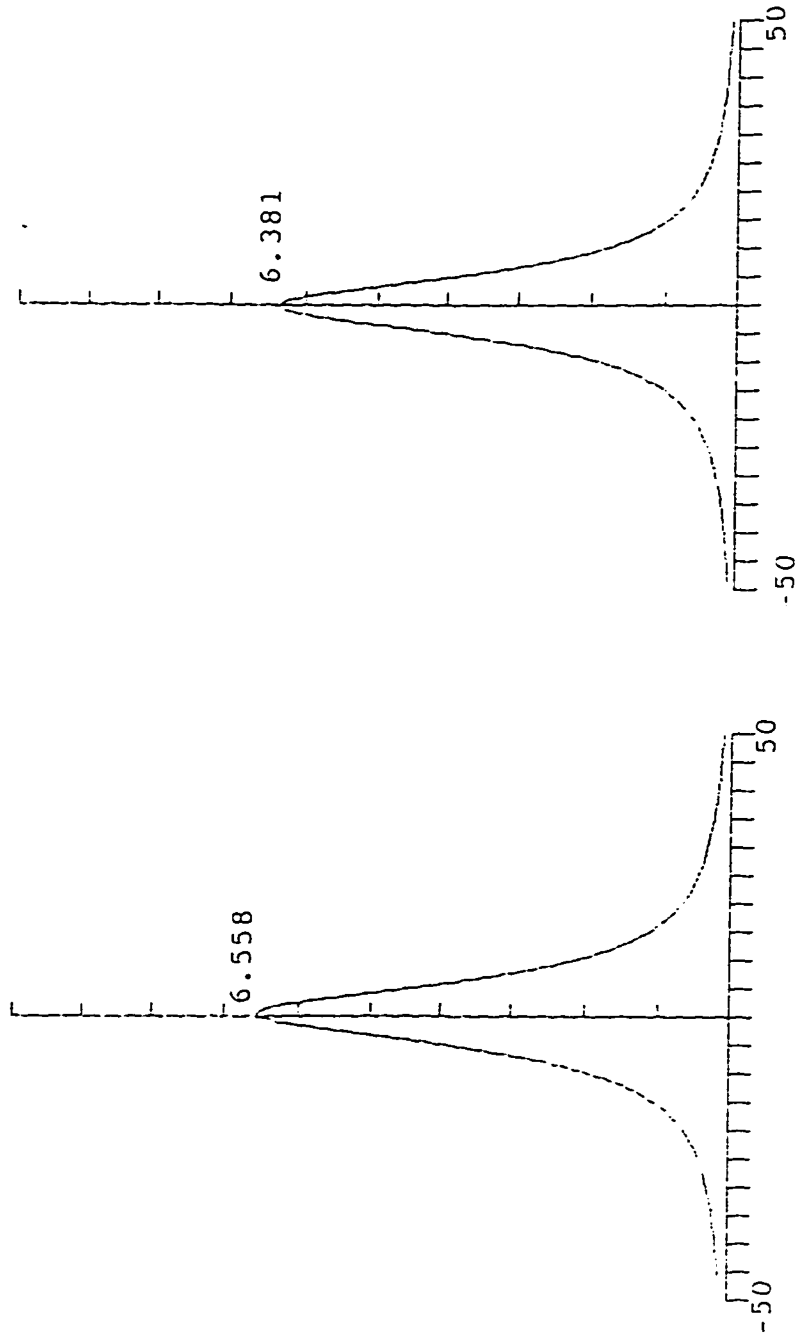


Figure 4.73: Plot for New Design Case (a), Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

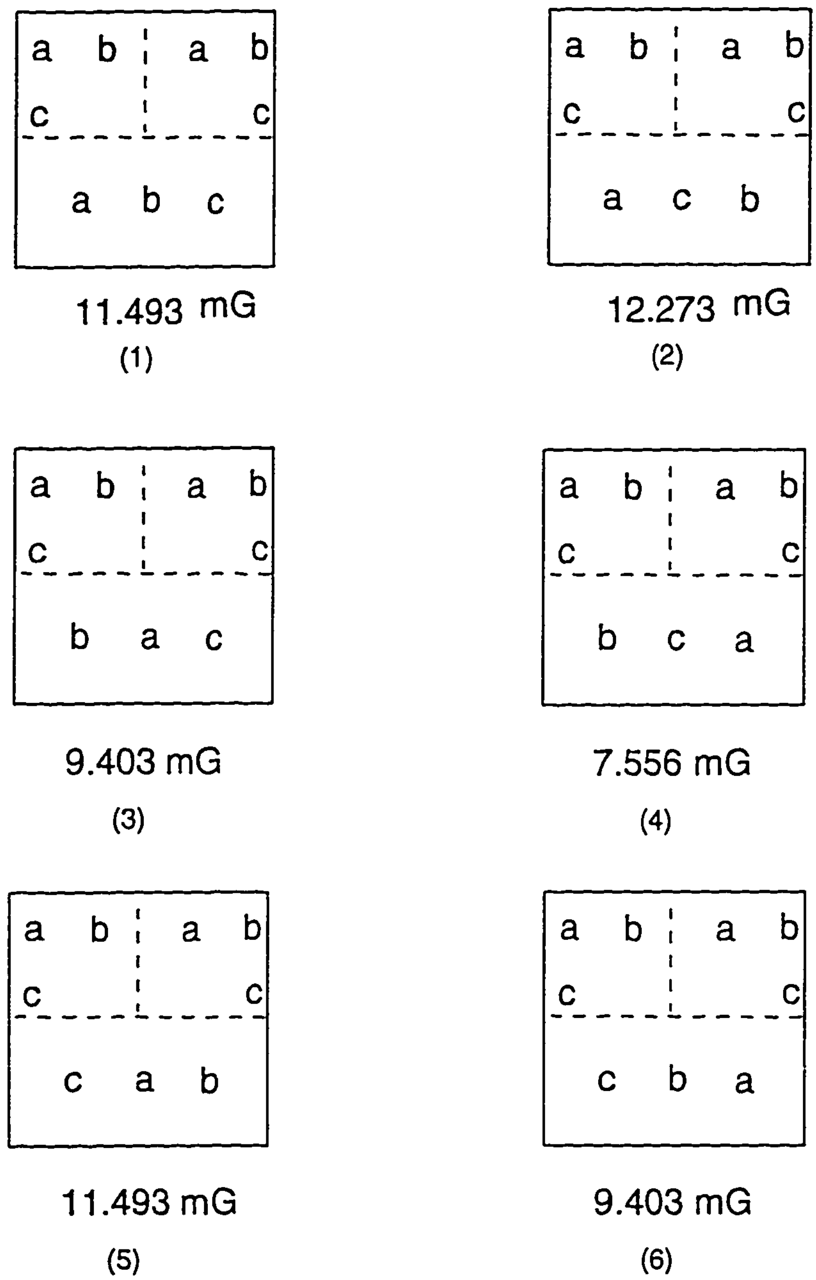
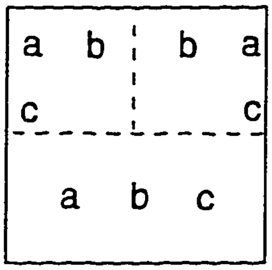
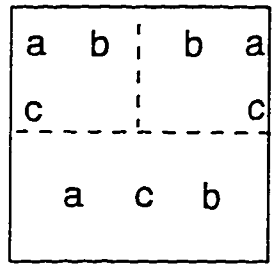


Figure 4.74: New Design Case (b) - Three Cables per Phase (9 conductors)



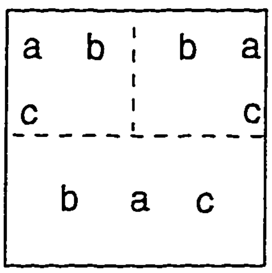
9.199 mG

(7)



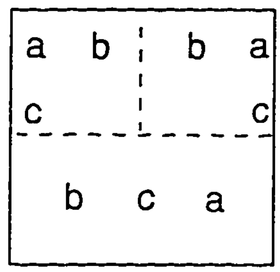
7.597 mG

(8)



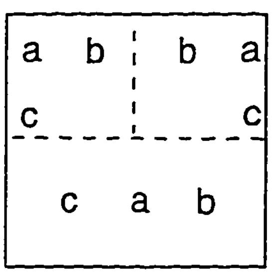
9.344 mG

(9)



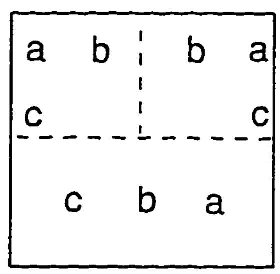
7.597 mG

(10)



9.344 mG

(11)



9.199 mG

(12)

Figure 4.75: New Design Case (b) - Three Cables per Phase (contd.)(9 conductors)

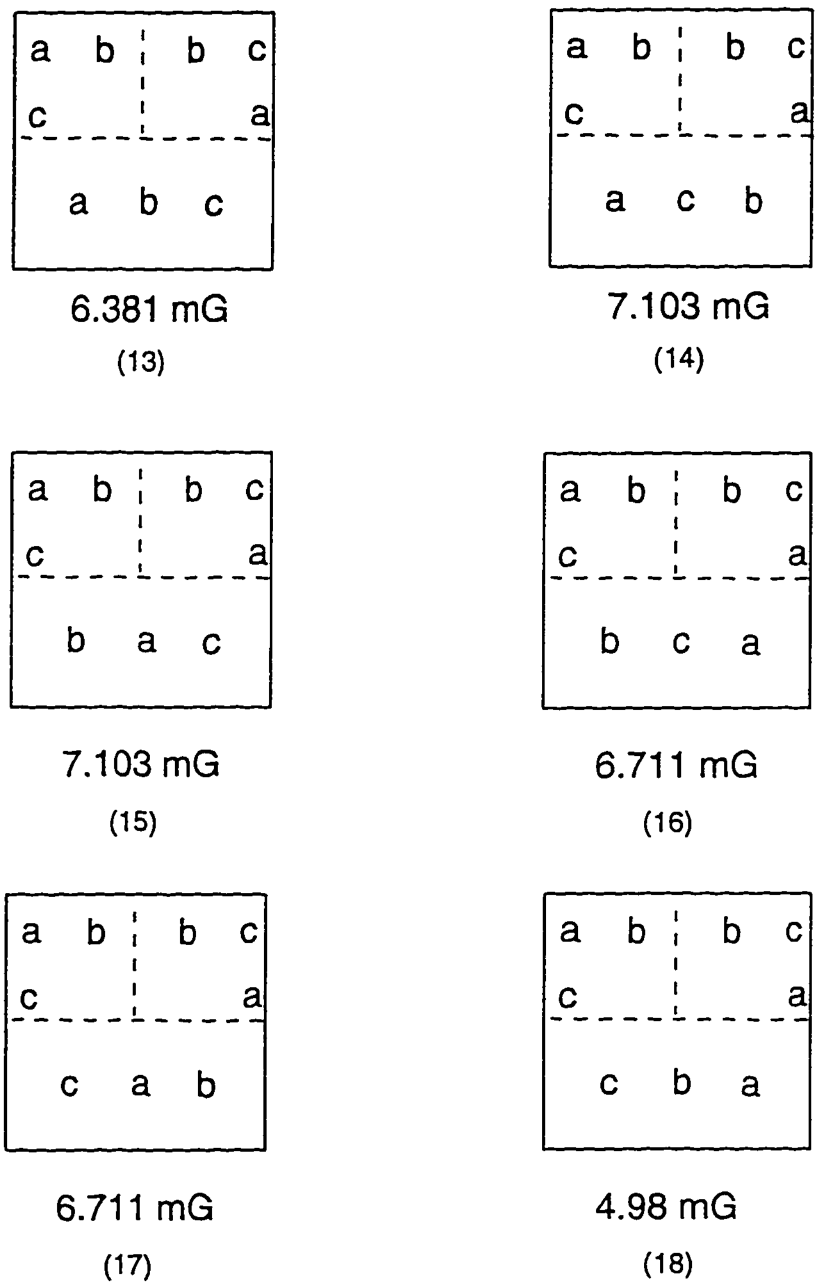


Figure 4.76: New Design Case (b) - Three Cables per Phase (contd.)(9 conductors)

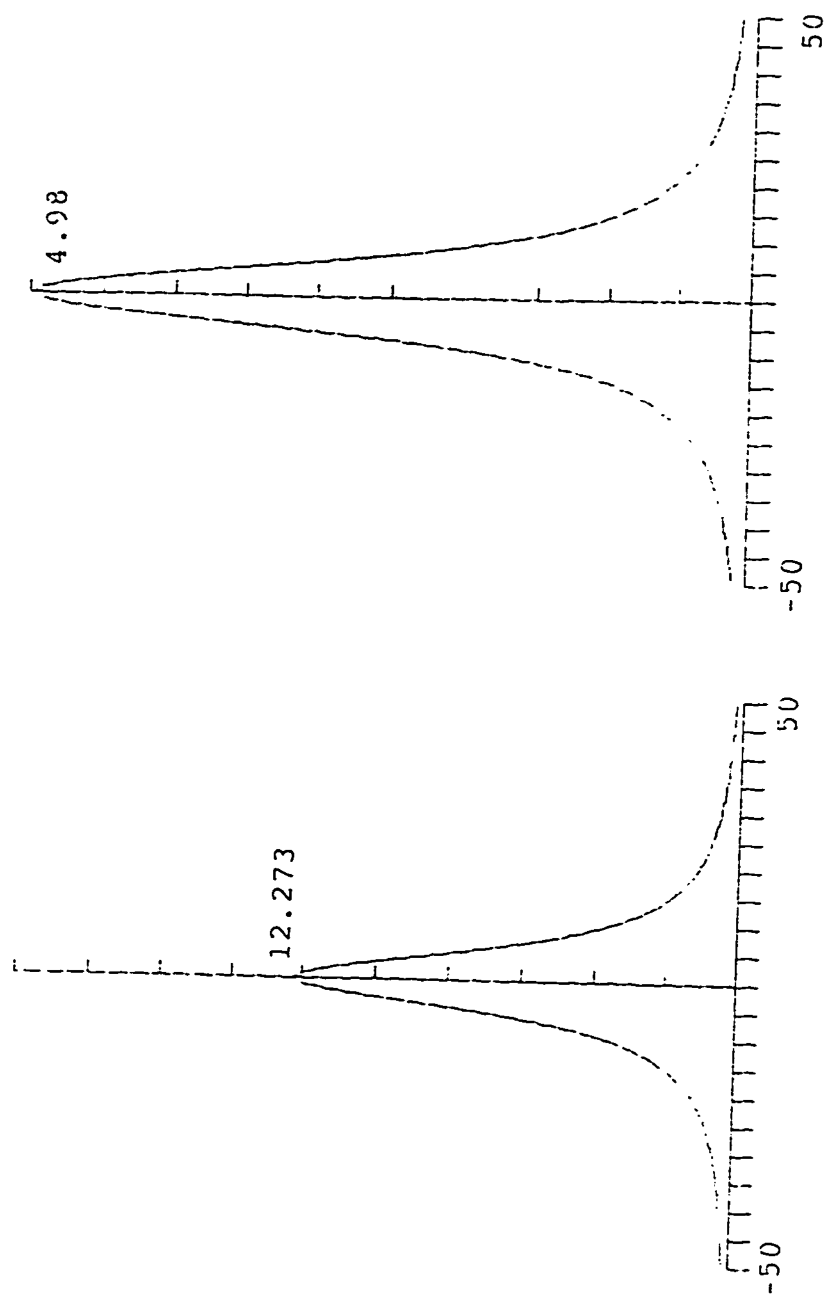


Figure 4.77: Plot for New Design Case (b), Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

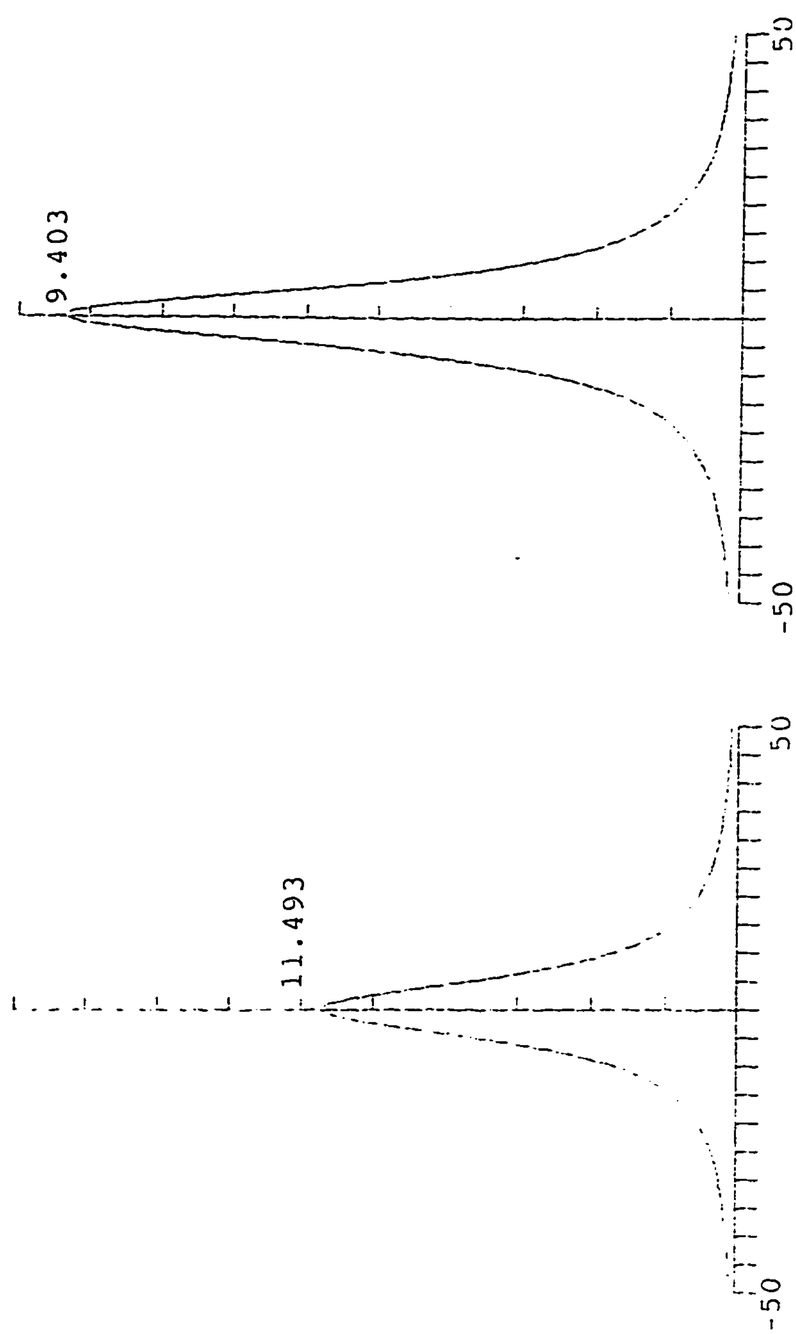


Figure 4.78: Plot for New Design Case (b), Three Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

4.3.4 Four cables per phase (12 conductors)

We have considered three different types of cable configuration namely, the flat, triangular and the stack for a single phase cable and flat and triangular for a three phase cable. The new design which we are proposing for a four cables per phase having 12 conductors is shown in Fig. 4.79. As we can see that the each set of three conductors are in a right angle configuration, and they can be folded on to the set of cables in the immediate vicinity. It means that the upper right half can be seen as the image of the lower right half or the upper left half and so on. There can also be imaging with respect to the diagonal sets i.e. the upper right half mapping on to the lower left half and the upper left half to the lower right half. The advantage of using such a configuration lies in the immense magnetic field cancellation as will be discussed in the following paragraphs and also that the vacant position in the structure can be used for the neutral conductors.

Different placement of the three phases for a 12 conductors configuration along with the simulated values of the maximum magnetic field are shown in cases (a) through (g) in Figs.4.80 and 4.81. A total of 12 conductors will generate a large number of combinations. To find the configuration it is not required to simulate all the cases. Having known from the 6 conductors case about the cancellation due to the image and the inverted image a few cases are tried and simulated.

In case (a) there is no imaging relation between any of the sets. The field for a 1.20 inch diameter of cable was found to be 11.94mG. The field for the same conductor current for a flat, stack and triangular configuration simulated in given in Table 4.5 is 0.783, 0.475 and 2.834 mG respectively. Hence, case (a) of this new design is worse than the EPRI's recommended configuration. Case (b)shows one image between the two top half and one inverted image formed between the two lower half set of conductor set and the lower left half. As evident the value comes down to 6.575 mG which is better than the triangular but still more than the flat and the stack. In case(c) the bus arrangement shows that each set is a mirror of the other, the left that of the right and the top that of the bottom. There is more cancellation here and the figure comes below to only 1.794 mG. The next configuration shows that the upper left half is an inverted image of the upper right one and the lower left half the inverted image of the lower right half.There are two images also present. The field obtained is now 1.56 mG, which proves that the inverted image increases the cancellation due to the other phases.

In Fig.4.81 the other three cases are shown. In case (e) there are two inverted images and two images. There is an inverted image between the top and the bottom and imaging between the left and the right. The field is now 1.553 mG and has marginally decreased as compared to the previous case. Case (f) shows that all the four halves are inverted image of each other and the field value has reduced to 1.546 mG. The minimum field which we obtain is for the last one shown in Fig.4.81 which is case (g). As we can see that the field is very very small, the value being only 0.014mG, which is less than all the three standard configurations. Here the diagonal sets are image of each other and gives the least field. The plots of all the 7 cases are shown in Figs. 4.82 to 4.85.

Hence, we can conclude that the new designs mentioned above are very useful from a magnetic field point of view with the suggested phase configurations. They are very low cost schemes that can be implemented easily. The others, for example increasing the depth and providing passive shielding involves a lot of cost.

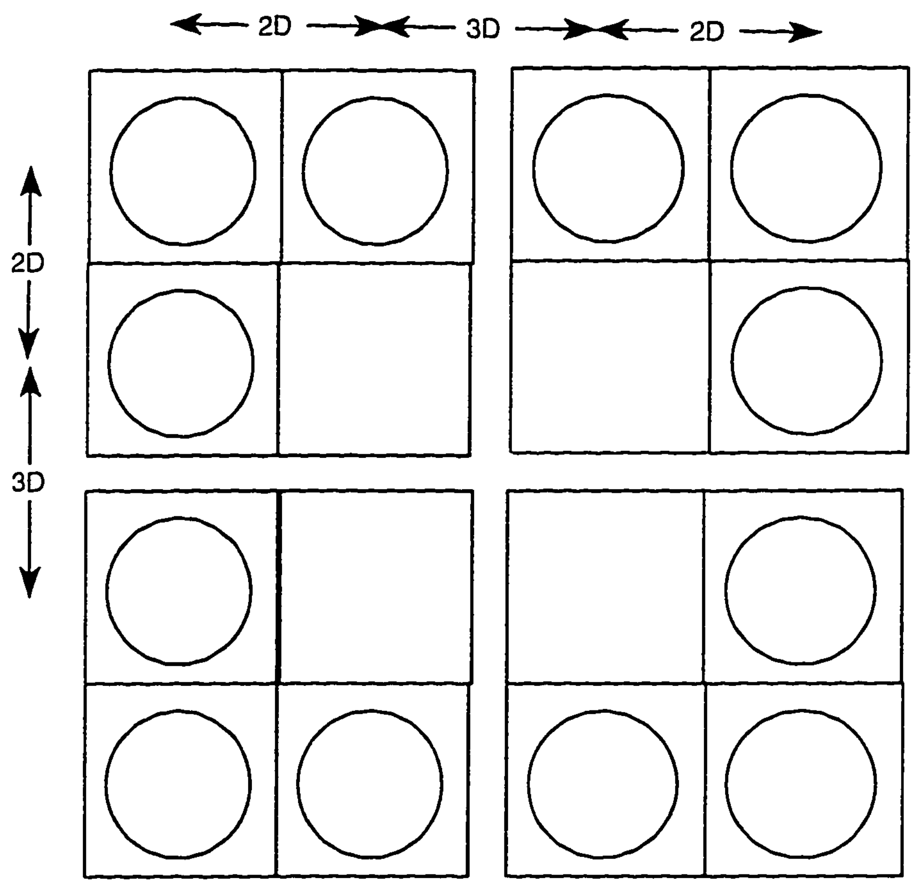


Figure 4.79: New Design - Four Cables per Phase (12 conductors)

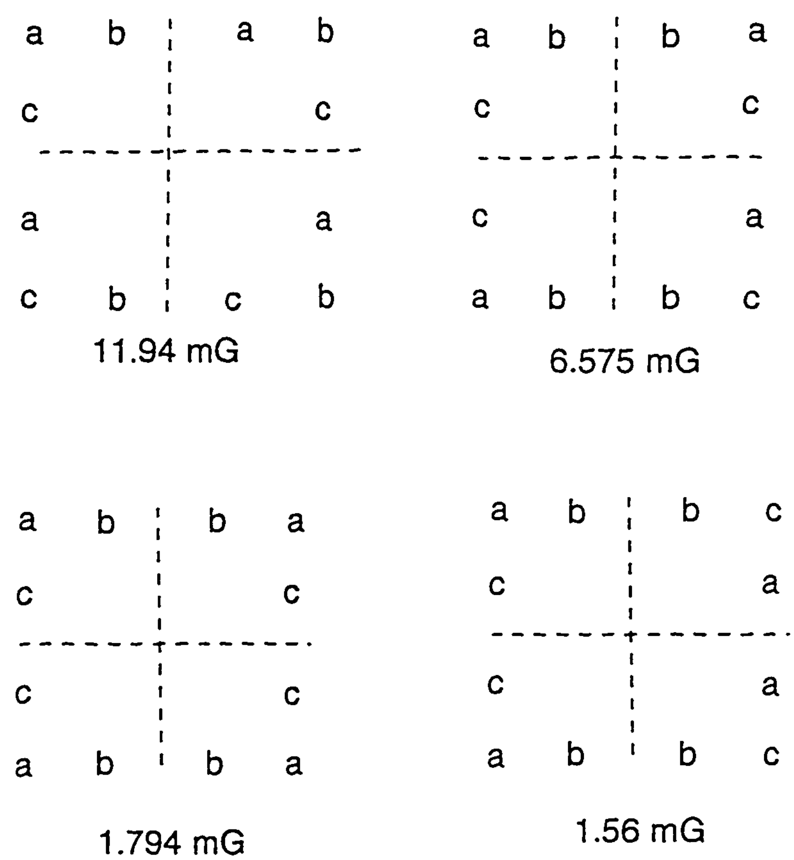


Figure 4.80: Results - Four Cables per Phase

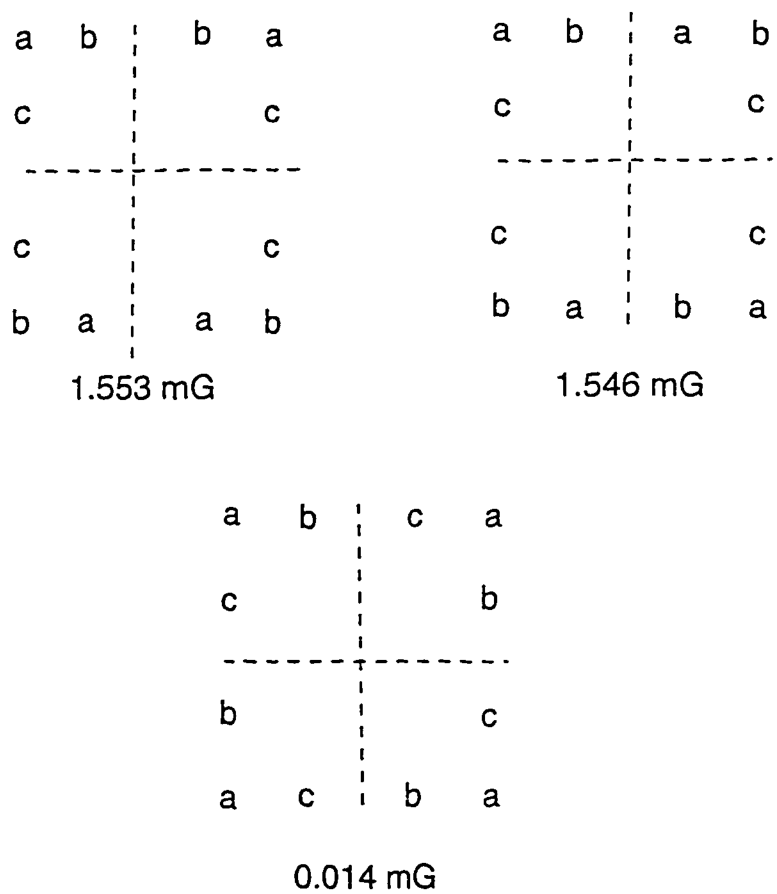


Figure 4.81: Results - Four Cables per Phase (Contd.)

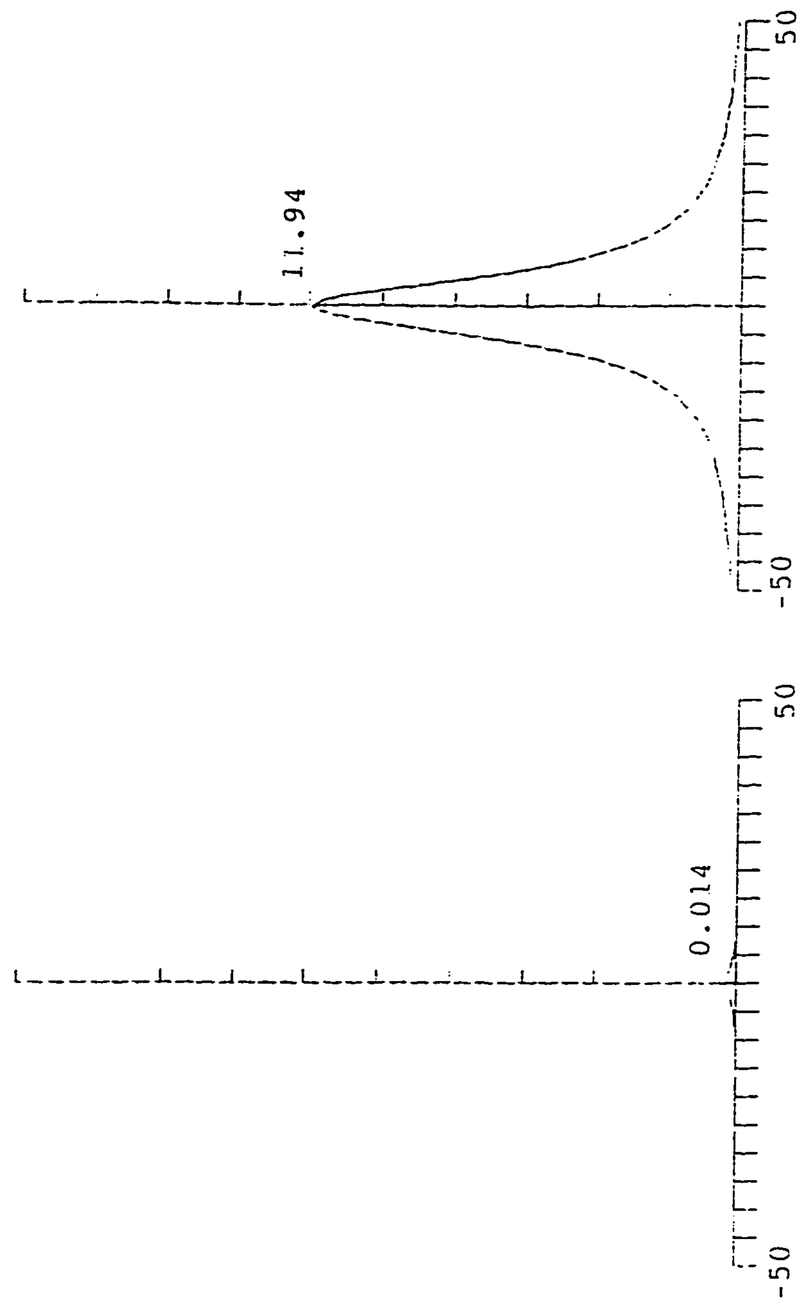


Figure 4.82: Plot for New Design, Four Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Best and Worst case

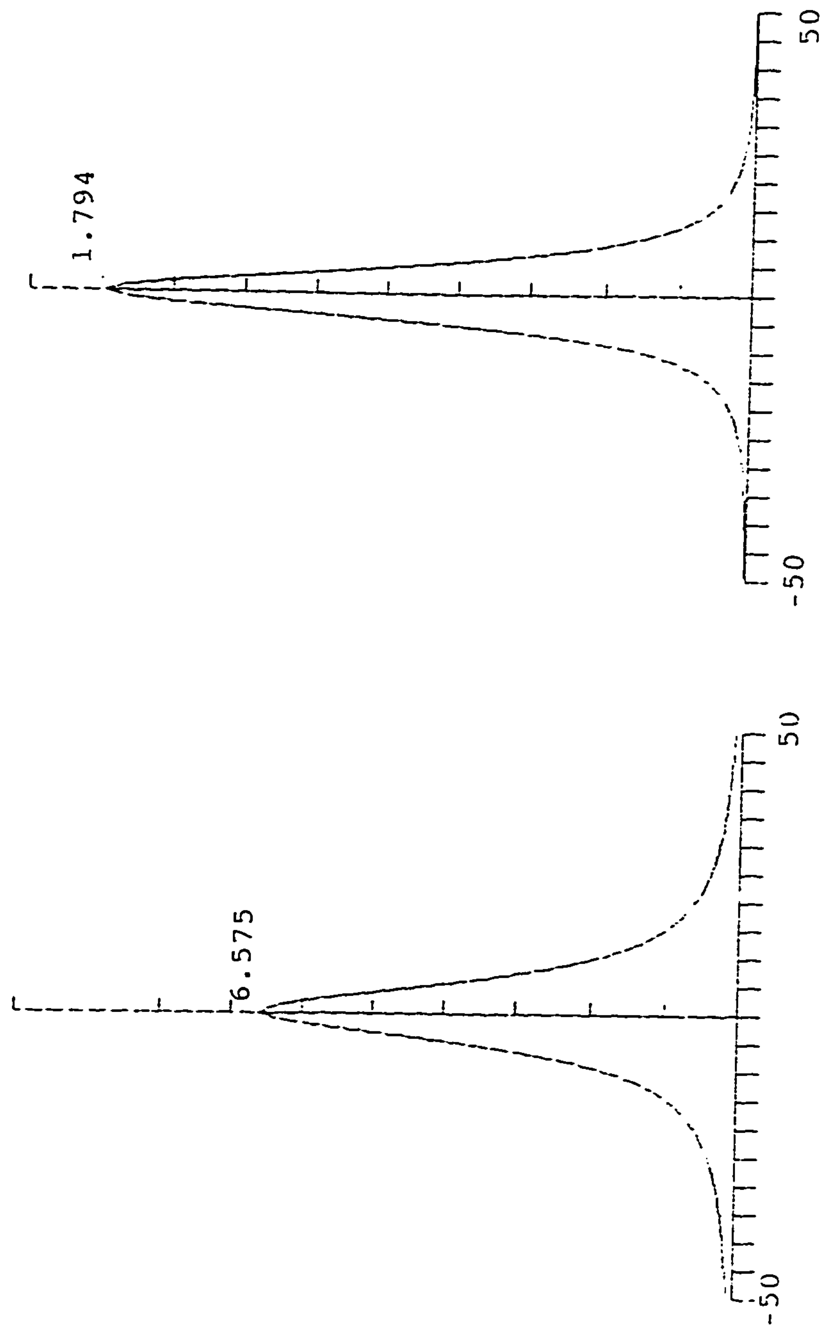


Figure 4.83: Plot for New Design, Four Cables per phase. Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

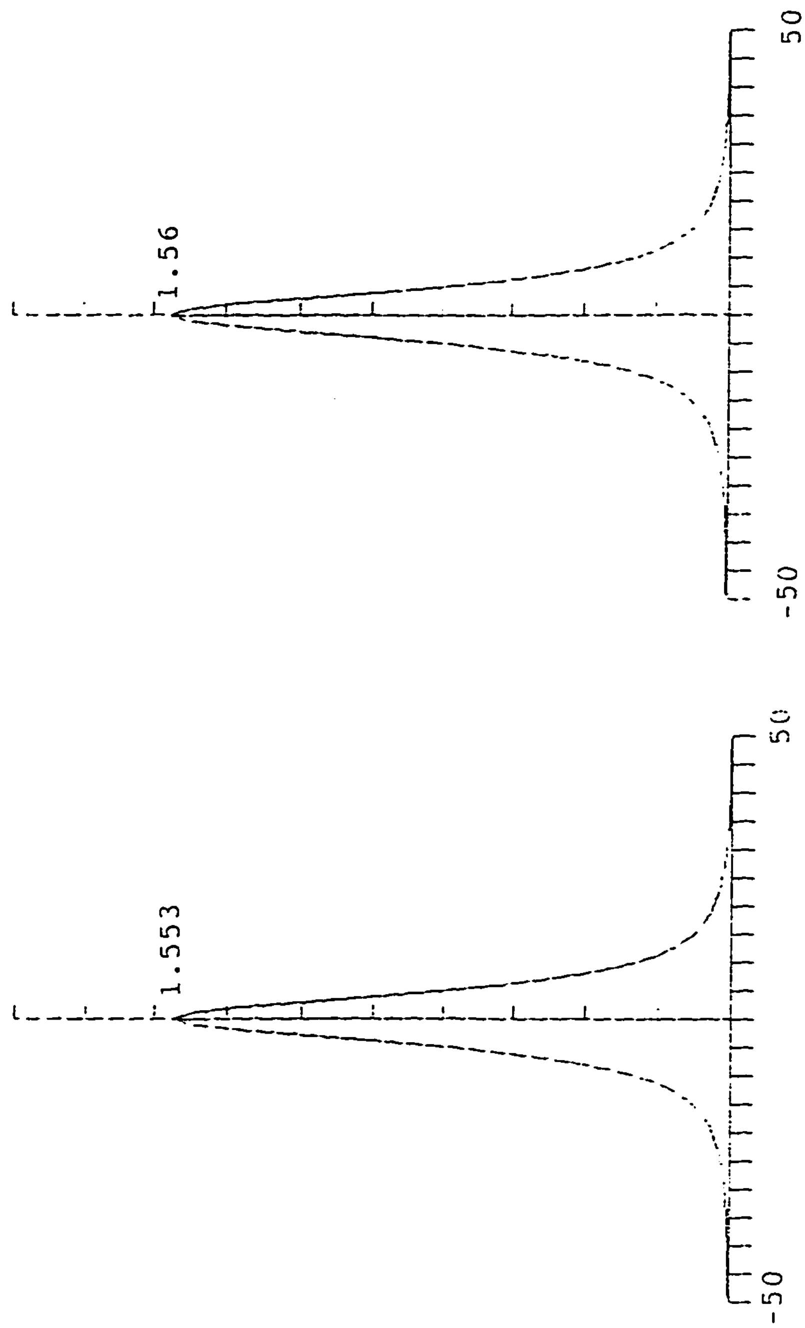


Figure 4.84: Plot for New Design, Four Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

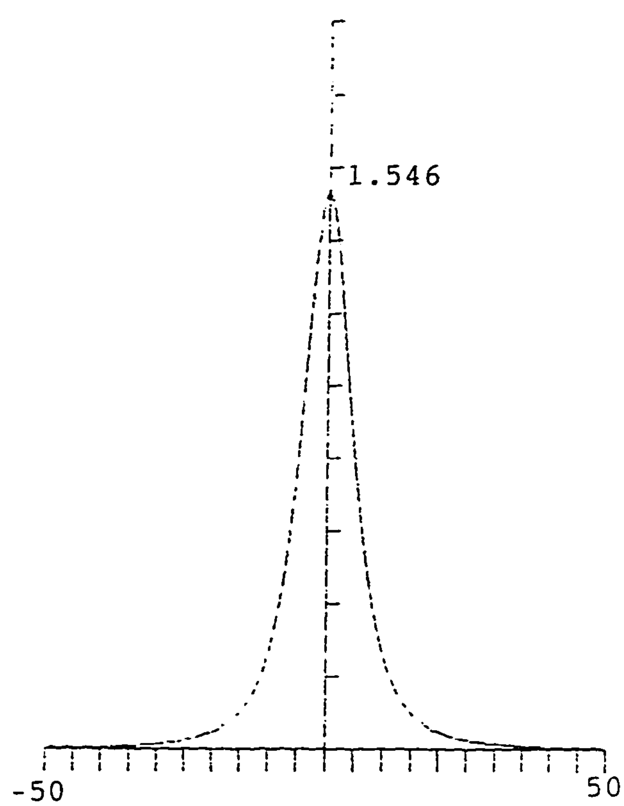


Figure 4.85: Plot for New Design, Four Cables per phase, Cable dia. 1.20 inch (Single Phase Cable), Intermediate cases

Chapter 5

Implementation of Shielding Principles

In chapter 3 the basics of the shielding schemes were discussed with particular emphasis on the passive shielding scheme. There are two types of shielding namely shielding the source and shielding the subject. Both these type are implemented in this thesis. One particular case of Active Shielding is also shown in the thesis, however the active shielding theory is not developed yet much.

5.1 Shielding the Source

The principle of passive shielding is applied on the sources which are single phase and three phase cables. All the different cases simulated in the previous chapter without shielding are being simulated here after shielding with the same material as the conductor itself. Five different plate thickness 0.005, 0.003, 0.01, 0.03 and 0.05 inches were taken and the field reduction were calculated. However, the results of only two plate thickness (0.005 and 0.03 inch) are reported here as the difference between them is not much. Three different cable sizes namely, #2/0, 500MCM and 1000MCM, having conductor dia. of 1.07, 1.55 and 1.89 inches were taken and selected. A 2 inch thickness for insulation was also incorporated. The results obtained shows significant reduction in the field values.

5.1.1 Single phase cables

The results for a single phase having different configurations and different number of circuits are tabulated in Tables 5.1 to 5.5. For a two cables per phase (Table 5.1), if we consider a 1.89 inch the field reduces from a level of 47.04 to only 0.97 and 0.98mG (stack configuration) for 0.005 and 0.03 inch shielding plate respectively. In terms of the shielding factor it is only 0.0206 which is very high reduction. For other cable dia. the reduction is generally of the comparable magnitude.

The simulated values does not necessarily correspond to the optimal conditions that have been obtained in the previous chapter. For a three cables per phase the shielding factor varies between 0.025 to 0.144 for the cases considered. The field value comes down to as low as only 2 - 3 % of the simulated value without shielding. In case of a four cables per phase the shielding factor is varying from 0.04 to 0.47. The lower the value of shielding factor the more effective the shielding is. The reductions in case of five and six cables per phase are shown on tables 5.4 and 5.5. The reductions are more pronounced for larger size of the cable. Another thing to notice here is that for a thicker plate generally the reduction is less. This is due to the fact that these plates are reducing the level of magnetic field over a particular region. Thicker plates generally reflect the fields closer to the source as compared to thinner plates. The region taken here is -50 to 50 ft. on either side of the reference axis which is generally the centre of the cable configuration. The plots showing the comparison between the shielded and the unshielded case for the stack, triangular and the flat layout are shown in Figs.5.1 to 5.3 for five cables per phase having a

Table 5.1: Maximum Value of Magnetic Field for two cables per phase(Single Phase Cables)

Cable Dia. (inch)	Plate thickn (inch)	Der. Curt. (A)	Without Shielding Stack (mG)	Without Shielding Tri (mG)	Without Shielding Flat (mG)	With Shielding Stack (mG)	With Shielding Tri (mG)	With Shielding Flat (mG)
1.07	0.005	87.5	8.74	4.4	0.901	0.48	0.59	0.58
1.07	0.03	87.5	8.74	4.4	0.901	0.50	0.66	0.66
1.55	0.005	190	27.14	13.71	4.07	0.67	0.98	0.48
1.55	0.03	190	27.14	13.71	4.07	0.68	1.0	0.49
1.89	0.005	272.5	47.04	23.72	8.62	0.97	1.45	0.55
1.89	0.03	272.5	47.04	23.72	8.62	0.98	1.47	0.56

cable dia. of 1.55 inch.

Table 5.2: Maximum Value of Magnetic Field for three cables per phase(Single Phase Cables)

Cable Dia. (inch)	Plate thickn (inch)	Der. Curt. (A)	Without Shielding			With Shielding		
			Stack (mG)	Tri (mG)	Flat (mG)	Stack (mG)	Tri (mG)	Flat (mG)
1.07	0.005	87.5	4.69	6.56	13.21	0.5	0.83	0.63
1.07	0.03	87.5	4.69	6.56	13.21	0.54	0.95	0.74
1.55	0.005	190.0	15.32	20.33	32.19	0.54	1.37	0.87
1.55	0.03	190.0	15.32	20.33	32.19	0.546	1.40	0.88
1.89	0.005	272.5	27.54	34.92	55.96	0.68	2.03	1.35
1.89	0.03	272.5	27.54	34.92	55.96	0.69	2.07	1.37

Table 5.3: Maximum Value of Magnetic Field for four cables per phase(Single Phase Cables)

Cable Dia. (inch)	Plate thickn (inch)	Der. Curt. (A)	Without Shielding			With Shielding		
			Stack (mG)	Tri (mG)	Flat (mG)	Stack (mG)	Tri (mG)	Flat (mG)
1.07	0.005	87.5	1.73	6.48	1.38	0.39	0.90	0.57
1.07	0.03	87.5	1.73	6.48	1.38	0.41	0.87	0.65
1.55	0.005	190.0	7.69	20.08	6.23	0.52	1.13	0.51
1.55	0.03	190.0	7.69	20.08	6.23	0.53	1.16	0.53
1.89	0.005	272.5	16.08	34.70	13.19	0.64	1.61	0.62
1.89	0.03	272.5	16.08	34.70	13.19	0.65	1.65	0.64

Table 5.4: Maximum Value of Magnetic Field for five cables per phase(Single Phase Cables)

Cable Dia. (inch)	Plate thickn (inch)	Der. Curt. (A)	Without Shielding Stack (mG)	Without Shielding Tri (mG)	Without Shielding Flat (mG)	With Shielding Stack (mG)	With Shielding Tri (mG)	With Shielding Flat (mG)
1.07	0.005	87.5	4.69	8.93	17.56	0.82	0.52	0.82
1.07	0.03	87.5	4.69	8.93	17.56	0.95	0.57	0.98
1.55	0.005	190.0	15.54	26.96	14.98	0.61	1.34	0.62
1.55	0.03	190.0	15.54	26.96	14.98	0.63	1.38	0.64
1.89	0.005	272.5	28.35	46.66	26.95	0.78	1.31	0.76
1.89	0.03	272.5	28.35	46.66	26.95	0.79	1.34	0.77

Table 5.5: Maximum Value of Magnetic Field for six cables per phase(Single Phase Cables)

Cable Dia. (inch)	Plate thickn (inch)	Der. Curt. (A)	Without Shielding Stack (mG)	Without Shielding Tri (mG)	Without Shielding Flat (mG)	With Shielding Stack (mG)	With Shielding Tri (mG)	With Shielding Flat (mG)
1.07	0.005	87.5	1.88	11.0	21.84	0.63	0.96	0.71
1.07	0.03	87.5	1.88	11.0	21.84	0.72	1.05	0.85
1.55	0.005	190.0	8.61	33.61	7.50	0.54	1.58	0.51
1.55	0.03	190.0	8.61	33.61	7.50	0.55	1.62	0.53
1.89	0.005	272.5	18.36	58.03	15.90	0.68	2.30	0.65
1.89	0.03	272.5	18.36	58.03	15.90	0.69	2.33	0.66

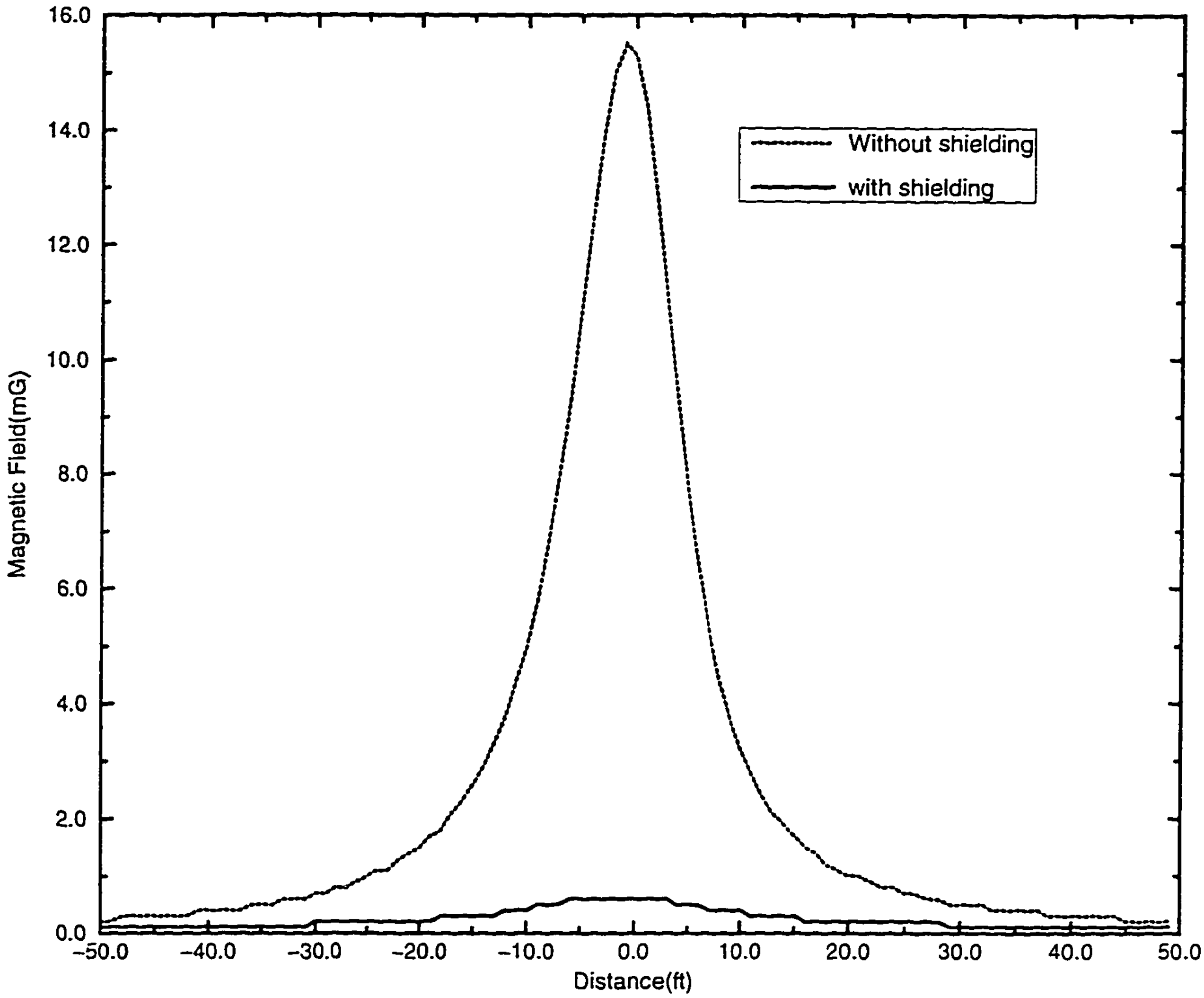


Figure 5.1: Comparison of Magnetic field values between with and without shielding for Stack Configuration (Cable dia.1.55 inch, Five cables per phase, Single Phase Cable)

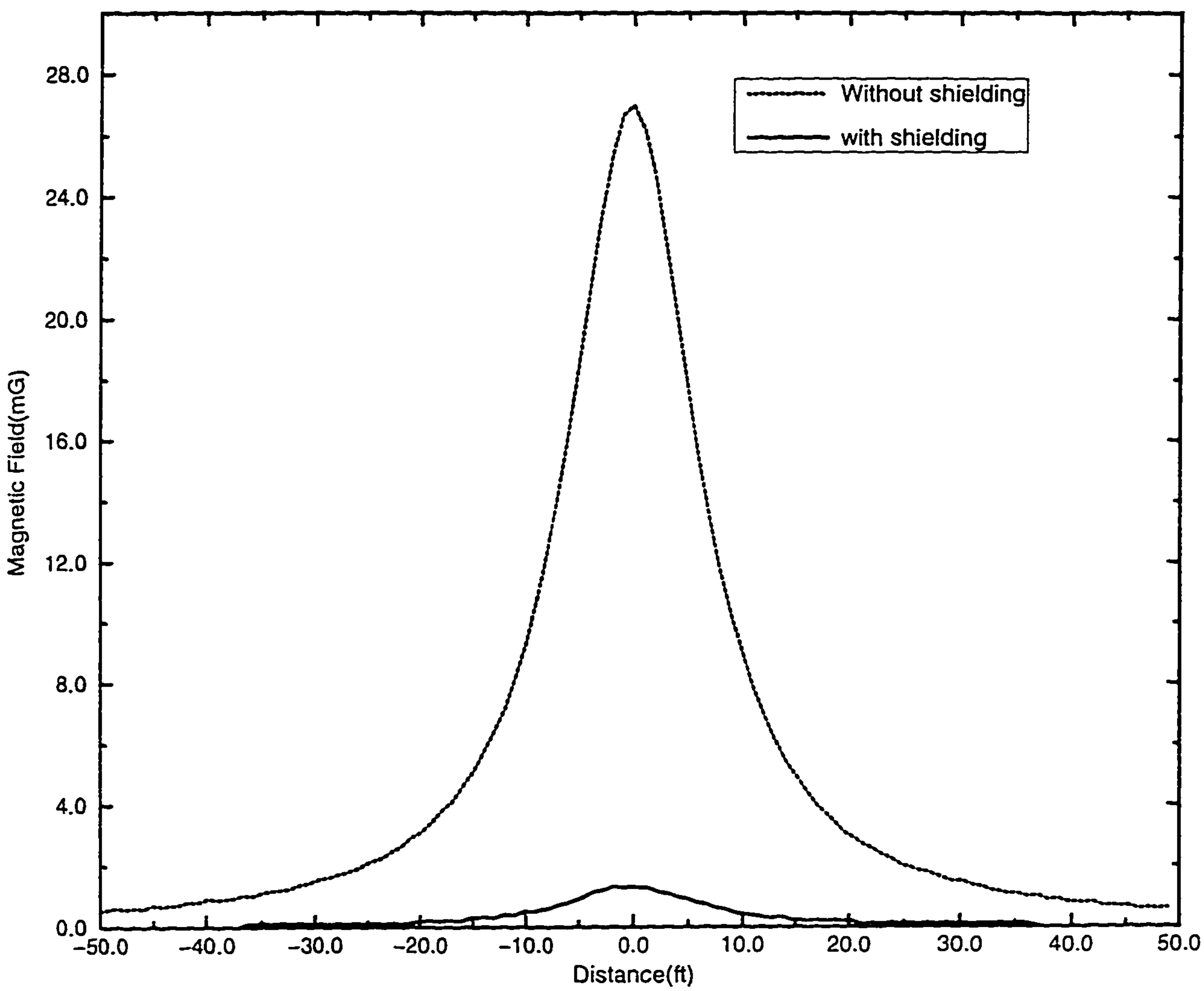


Figure 5.2: Comparison of Magnetic field values between with and without shielding for Triangular Configuration (Cable dia.1.55 inch, Five cables per phase, Single Phase Cable)

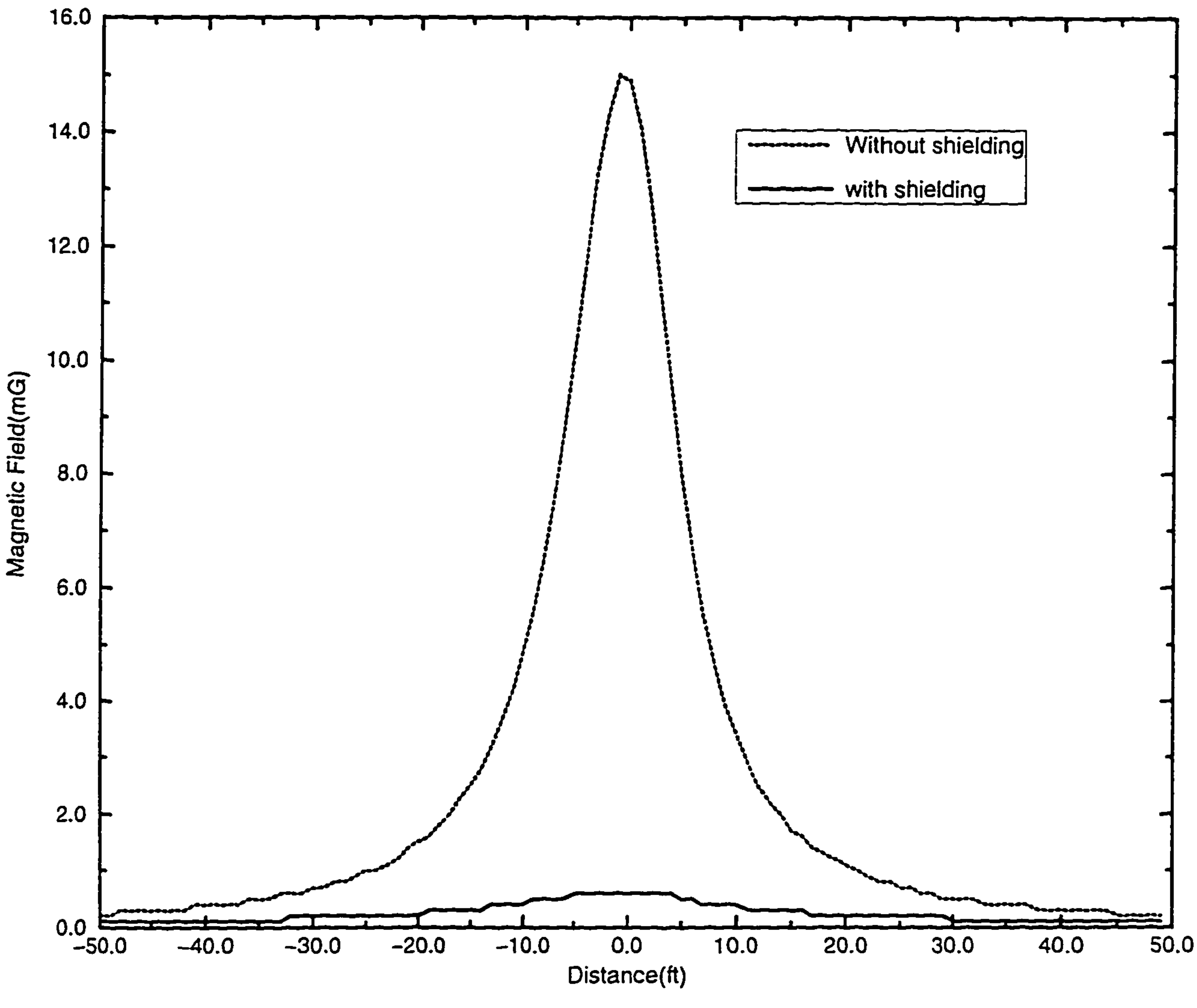


Figure 5.3: Comparison of Magnetic field values between with and without shielding for Flat Configuration (Cable dia.1.55 inch, Five cables per phase, Single Phase Cable)

5.1.2 Three phase cables

For a three phase cable two type of configurations the flat and the triangular are simulated. The configurations chosen here does not always correspond to the phase locations that gives the minimal field. To be precise other than two cables per phase all the configurations of flat arrangement are not the optimal conditions. For triangular the values are the minimum possible one could get out of the phase relations. Tables 5.6 to 5.10 shows the values of magnetic fields before and after shielding for 1.07, 1.55 and 1.89 inch diameter cable. In the case of a double circuit line table 5.6 gives the values before and after shielding. As evident from the table the reduction in the field level varies between 8 - 92 %. For a three cables per phase line the reduction ranges between 85 - 95 %. In the case of four cables per phase again the maximum reduction is 95%. The reduction is more generally in the case of a thinner plate but the difference is not much. In some of the cases of triangular configuration the thicker plates give less fields. This is due to a different configurations of the conductor arrangements.

For five cables per phase and six cables per phase also the level of reductions obtained is very high and this leads us to conclude that the passive shielding scheme of magnetic field reduction is a very successful technique but at an extra cost. Also this cannot be applied to the existing system. Only to a new system this scheme can be applied at an extra cost. The plots showing the comparison between the shielded and the unshielded case for the flat and the triangular layout are shown in Figs.5.4 and 5.5 for five cables per phase having a cable dia. of 1.55 inch.

Table 5.6: Maximum Value of Magnetic Field for two cables per phase(Three Phase Cables)

Cable Diameter (inch)	Plate thickness (inch)	Derated Current (A)	Without Shielding Flat (mG)	Without Shielding Triangular (mG)	With Shielding Flat (mG)	With Shielding Triangular (mG)
1.07	0.005	87.5	0.321	4.379	0.297	0.525
1.07	0.03	87.5	4.379	0.297	0.307	0.54
1.55	0.005	190.0	1.456	13.604	0.529	1.111
1.55	0.03	190.0	1.456	13.604	0.523	1.115
1.89	0.005	272.5	2.698	23.586	0.788	2.941
1.89	0.03	272.5	2.698	23.586	0.759	2.647

Table 5.7: Maximum Value of Magnetic Field for three cables per phase(Three Phase Cables)

Cable Diameter (inch)	Plate thickness (inch)	Derated Current (A)	Without Shielding Flat (mG)	Without Shielding Triangular (mG)	With Shielding Flat (mG)	With Shielding Triangular (mG)
1.07	0.005	87.5	6.675	6.543	0.965	0.653
1.07	0.03	87.5	6.675	6.543	1.082	0.672
1.55	0.005	190.0	20.762	20.242	1.233	1.452
1.55	0.03	190.0	20.762	20.242	1.276	1.442
1.89	0.005	272.5	35.937	34.96	1.719	3.571
1.89	0.03	272.5	35.937	34.96	1.754	3.621

Table 5.8: Maximum Value of Magnetic Field for four cables per phase(Three Phase Cables)

Cable Diameter (inch)	Plate thickness (inch)	Derated Current (A)	Without Shielding Flat (mG)	Without Shielding Triangular (mG)	With Shielding Flat (mG)	With Shielding Triangular (mG)
1.07	0.005	87.5	6.586	8.677	0.879	0.776
1.07	0.03	87.5	6.586	8.677	0.964	0.797
1.55	0.005	190.0	20.525	26.689	1.266	1.712
1.55	0.03	190.0	20.525	26.689	1.304	1.718
1.89	0.005	272.5	35.59	45.853	1.785	4.66
1.89	0.03	272.5	35.59	45.583	1.816	4.215

Table 5.9: Maximum Value of Magnetic Field for five cables per phase(Three Phase Cables)

Cable Diameter (inch)	Plate thickness (inch)	Derated Current (A)	Without Shielding Flat (mG)	Without Shielding Triangular (mG)	With Shielding Flat (mG)	With Shielding Triangular (mG)
1.07	0.005	87.5	8.831	10.772	1.203	0.895
1.07	0.03	87.5	8.831	10.772	1.326	0.918
1.55	0.005	190.0	27.58	24.238	1.625	1.85
1.55	0.03	190.0	27.58	24.238	1.677	1.75
1.89	0.005	272.5	47.915	41.734	2.251	7.207
1.89	0.03	272.5	47.915	41.734	2.297	6.375

Table 5.10: Maximum Value of Magnetic Field for six cables per phase(Three Phase Cables)

Cable Diameter (inch)	Plate thickness (inch)	Derated Current (A)	Without Shielding Flat (mG)	Without Shielding Triangular (mG)	With Shielding Flat (mG)	With Shielding Triangular (mG)
1.07	0.005	87.5	11.039	12.818	1.466	1.008
1.07	0.03	87.5	11.039	12.818	1.64	1.003
1.55	0.005	190.0	34.391	31.061	1.822	1.755
1.55	0.03	190.0	34.391	31.061	1.884	1.714
1.89	0.005	272.5	59.611	53.581	2.487	5.43
1.89	0.03	272.5	59.611	53.581	2.54	4.9

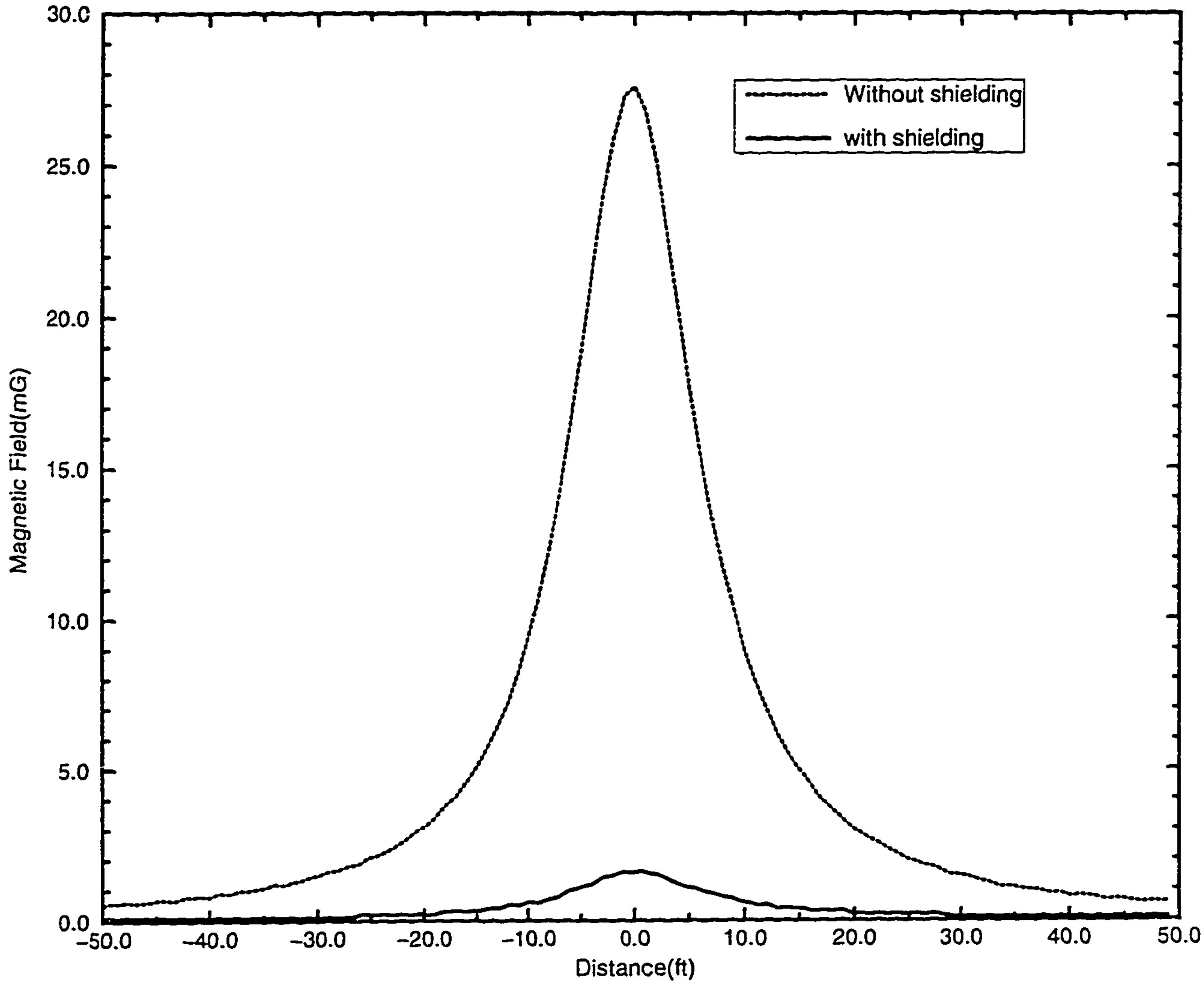


Figure 5.4: Comparison of Magnetic field values between with and without shielding for Flat Configuration (Cable dia.1.55 inch, Five cables per phase, Three Phase Cable)

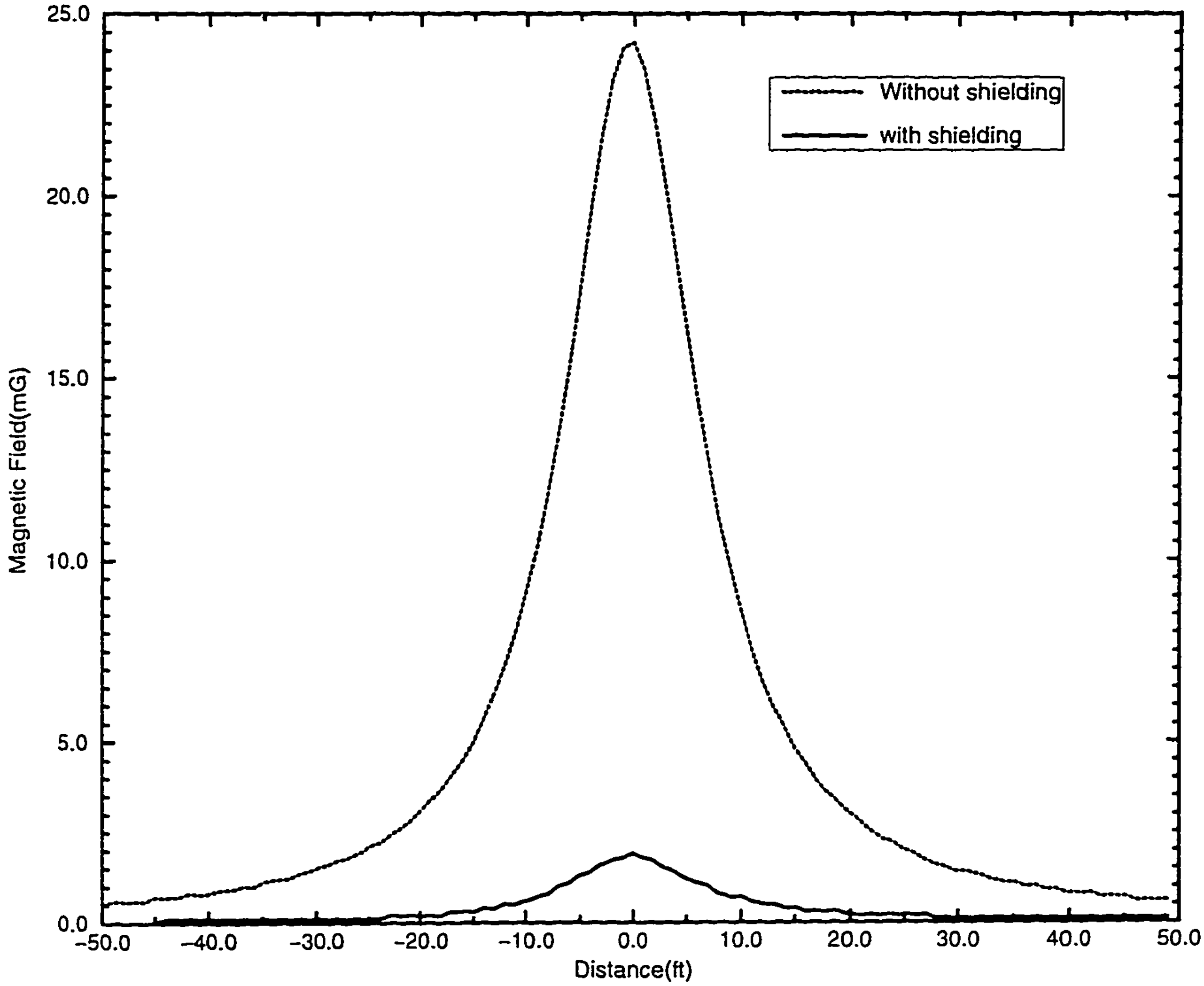


Figure 5.5: Comparison of Magnetic field values between with and without shielding for Triangular Configuration (Cable dia.1.55 inch, Five cables per phase, Three Phase Cable)

5.1.3 Active Shielding

The theory of active shielding is still in its early stage and very little work has been done in this area. However, one case of simulation result is shown here. The cable size selected is 1000MCM having a diameter of 1.89 inch. The rated current for this size of the cable is 550 amps and a 50% derating is applied on this rating of the current. The shield current is taken as 10% of the derated conductor current. The simulation is performed for a two cables per phase (Single Phase Cable) having stack configuration. The phase location does not correspond here for minimum field. The results are tabulated in Table 5.11. As evident from the results, the minimum field is obtained when the shield current direction is opposite to the conductor current and have the same phase sequence as the conductor. The value obtained is 2.065 mG, while for the same case when its not shielded the field value was found to be 2.295 mG. Hence, there is a reduction of about 10%. The plot of the best and the worst case is shown in Fig. 5.6.

Table 5.11: Result for Active Shielding for two cables per phase, Cable dia. 1.89 inch (Single Phase Cable)

Cable Diameter (inch)	Conductor Current (A)	Shield Current (A)	Shield Angle			Mag.field Values (mG)
			a (deg)	b (deg)	c (deg)	
1.89	272.5	27.25	0	0	0	165.683
1.89	272.5	-27.25	0	0	0	167.014
1.89	272.5	27.25	0	-120	-240	2.524
1.89	272.5	-27.25	0	-120	-240	2.065
1.89	272.5	27.25	0	120	240	2.431
1.89	272.5	-27.25	0	120	240	2.211

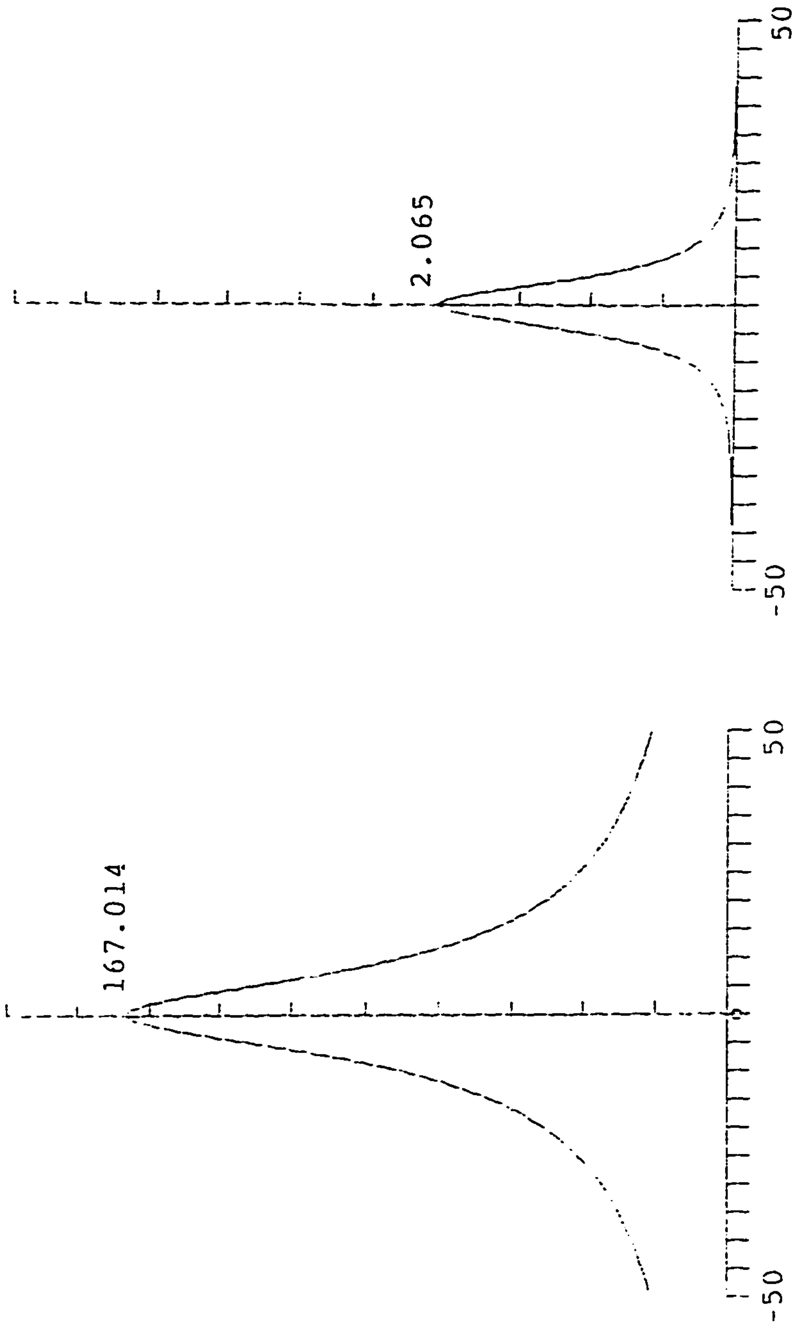


Figure 5.6: Plot of the best and worst case for Active Shielding for Stack Configuration (Cable dia.1.89 inch, Two cables per phase, Single Phase Cable)

5.2 Shielding the Subject

5.2.1 Simulation methodology

The software MAGNETO uses the boundary element method (BEM) for calculation of field distributions. Basically, this software is used to help solve the specific problems inherent in the design and analysis of magnetic equipment.

We have tried to use this package to see the effects of shielding using different magnetic materials having different geometries of plates. The method adopted here is as follows:

- The first step is the setting of the limits for different quantities. The default setting is the System International (SI) system of units. In our case we are using the USA system where length is expressed in inches and magnetic field in Gauss.

- The next step in the problem is to define the the geometry of the problem. Here, first of all the limits for X_{min}, Y_{min} and X_{max} are defined.Limits selected should be sufficient to accommodate the problem. Then there is the setting of the grid size. In our case we have taken it to be unity. This is followed by starting to draw the geometry of the whole problem.The conductors are defined by circle here whose co-ordinates are entered. The radius chosen here is 1.20 inch and the distance between the conductors within a set equal to 2.0D. To define the geometry of the shielding plates the line command is used and its location are entered starting from one point and coming back to the same point so as to get a closed plate.

- Once the geometry of the problem is complete currents are assigned to the conductors. A current of magnitude 115.0 amps is taken here for each conductor.In this package the phase angle cannot be entered and as such the analysis for only d.c.is possible.

- In the program a table for materials along with their permeabilities is present. One can add any new material which is not in the list and enter its permeability value. Then the materials are placed in their appropriate regions. Copper is selected here for the conductor and for plates we are taking Ferrite, Aluminum and Cast Iron in different cases as shown in the results.

- The last thing to define before doing the analysis is to place the boundary elements. Proper distribution of boundary is crucial to achieve valid results. No element are required at the interface of materials having the same permeability value.

The problem is now complete and is ready for the analysis. The contour (very fine density) map and the profiles diagram of the x-component of fields are plotted and are attached here.

5.2.2 Results and discussion

Different cases of shielding with different plate geometry and different materials are simulated as per the procedure explained in the above section. The results of eight different cases are documented in this thesis work.

In Case 1 two rectangular plates having a thickness of 0.3 inches and separated by 1 inch from each other are used for shielding purpose. The upper plate is of ferrite having a permeability of 2000 and is at a distance of 6 inches from the conductors. The lower plate is of Aluminum (relative permeability = 1.0). The contour map for this is shown in Fig. 5.7. The lower plate practically traps all the field, the ends of the plates being stressed more. The profile graph (refer to Fig. 5.8) shows the peak corresponding to the conductor locations. The arrow diagram shows the direction of movement of magnetic lines of force (refer to Fig. 5.9). In Case 2 the position of the two plates are interchanged, the field easily passing through the lower plate which is of Aluminum . It does practically no shielding and only the second line of defense which is ferrite helps in trapping the fields (refer to Fig. 5.10). The profile plot of this is shown in Fig. 5.11 where the peaks correspond to about a field value of 16 Gauss.

In the next case (Case 3) two high permeable materials ferrite and cast iron (relative permeability 165.96) plates are placed one over the other. Ferrite is farther away from the conductor. As evident from the contour map (Fig. 5.12 some of the fields are trapped by the lower plate and the rest by the ferrite plate. The contour of x - component of field are diverted away to the surroundings. Fig.5.13 shows the profile plot for this case. Next in Case 4 the positions of the two plates are interchanged. Fig. 5.14 shows that the lower high permeable plate does most of the trapping. The upper plate of cast iron takes care of the rest so that the region behind it perfectly safe to work. Moreover, the field near the conductor surface are not diverted to the surroundings as in the previous case. Therefore, it is better to keep the high permeable plate near to the conductor in case of multilayer shielding. Profile diagram for this case is plotted as before and shown in Fig. 5.15.

Case 5 (refer to Fig. 5.16) shows three level of plates with an air gap in the middle plate. The middle plate is of Aluminum having an air gap while the the top and the bottom plates of highly permeable Ferrite. The lower plate traps some of the field while the Aluminum does little to reduce the field in a particular region. The upper ferrite plate diverts some of these into other regions. If the positions of the plates are interchanged leading to Case 6 (refer to Fig. 5.18) the situation is much better as compared to the previous case. Gaps in shielding greatly affects the field. The ferrite plate which is at the middle provides a good shielding to the region of interest. The ends of the plates gets stressed more. The lower Aluminum plate does nothing to the field and it simply passes through it. The profile diagram for these two cases (Case 5 and 6) are shown in Figs. 5.17 and 5.19.

In Case 7 a single plate of ferrite is used for shielding but with an inverted U-shape. This will shield the conductors from three sides. The contour plot shown in Fig. 5.20 shows that the bend points are more stressed and it gives a better shielding performance. The profile plot for this case is shown in Fig. 5.21 shows that there is not much change in the profiles over the regions. In Case 8 the conductors are shielded from all the four sides by the ferrite plate of the same thickness. This leads to perfect shielding as the magnetic field obtained is static one. The profile plot for this is shown in Fig. 5.22.

Hence, we can conclude that a high permeability material can shield the subject of interest to a satisfactorily level and the areas can be safe from the health hazards associated with the magnetic field.

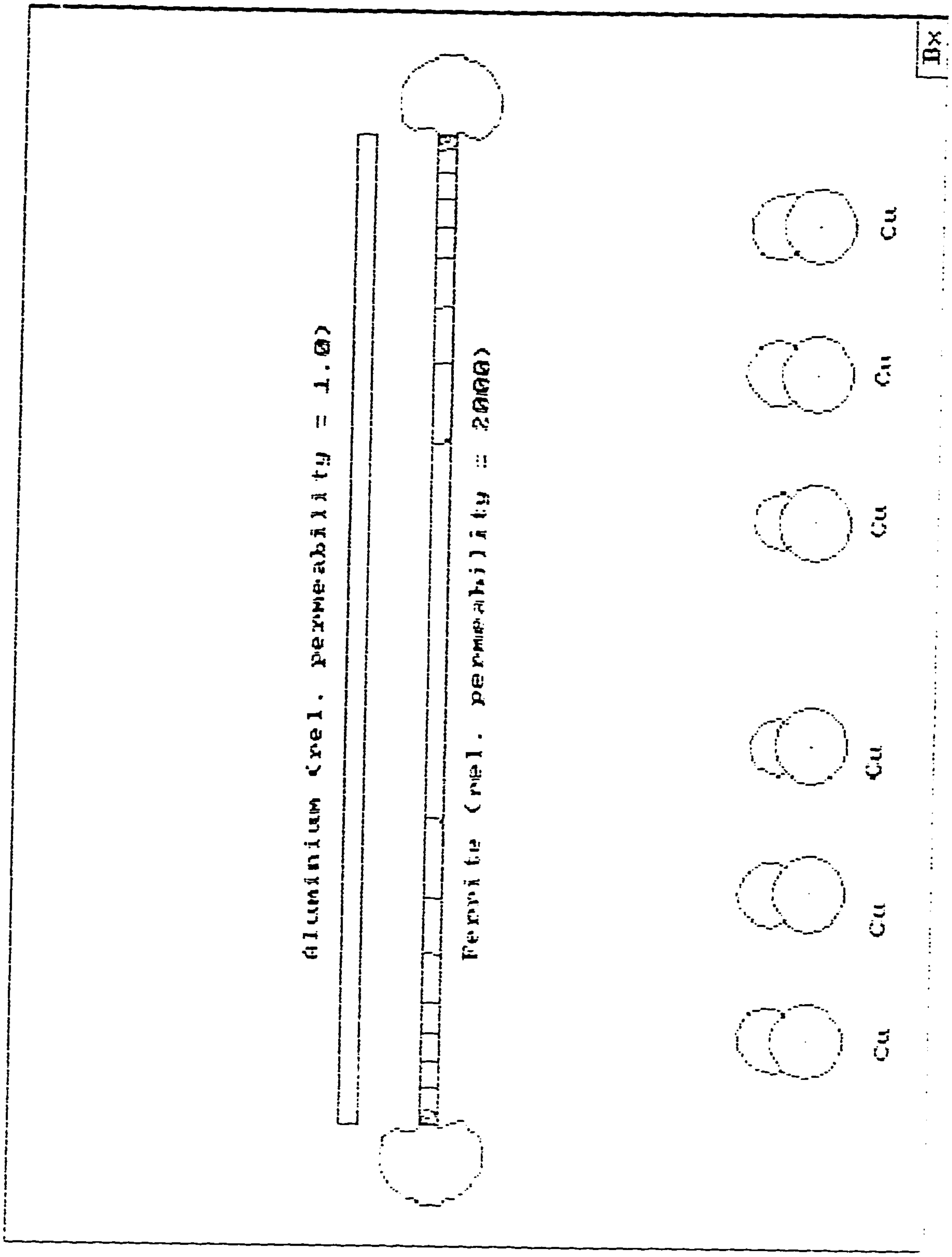


Figure 5.7: Contour Map(very fine density) - Case 1

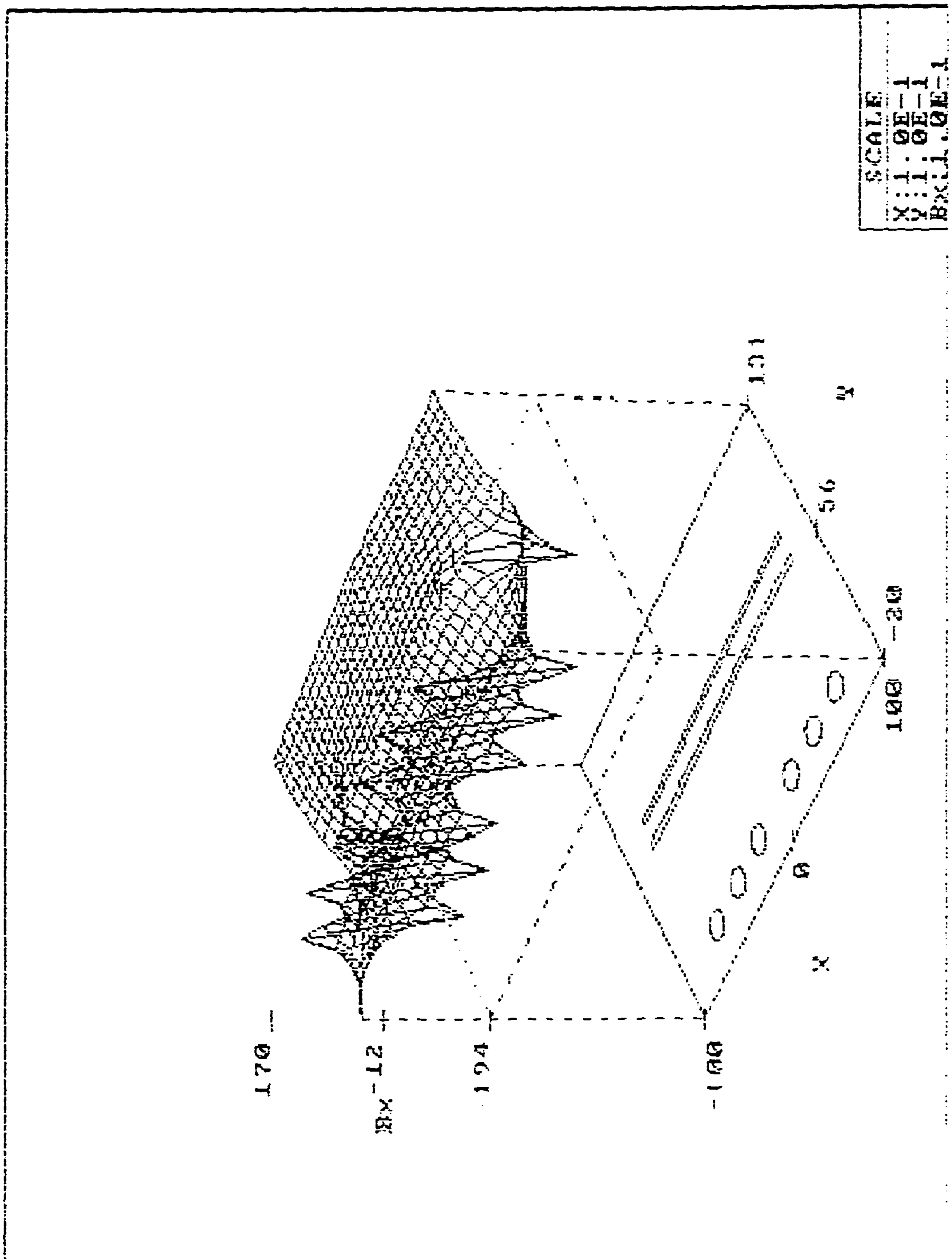


Figure 5.8: Profile Graph - Case 1

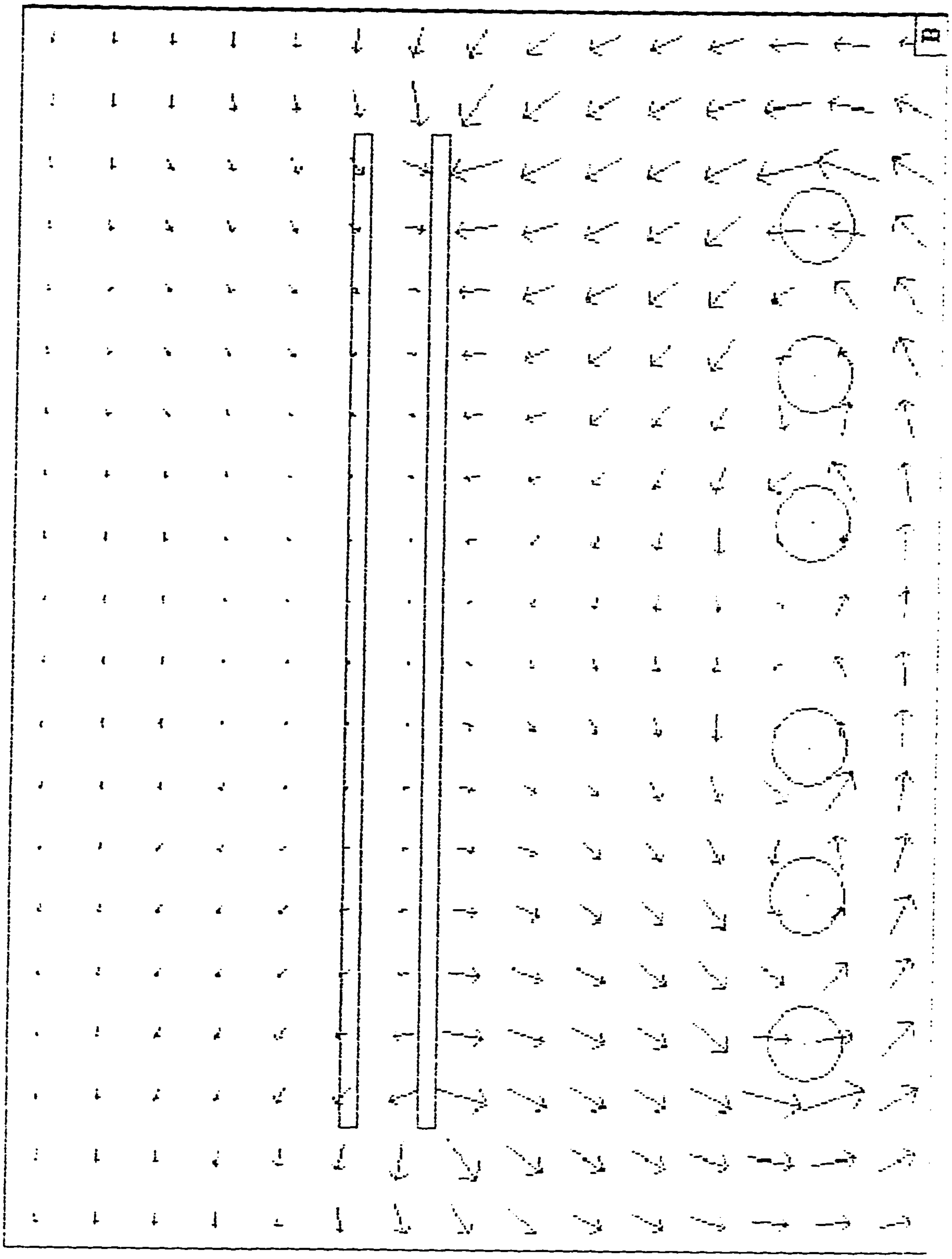


Figure 5.9: Arrow Diagram - Case 1

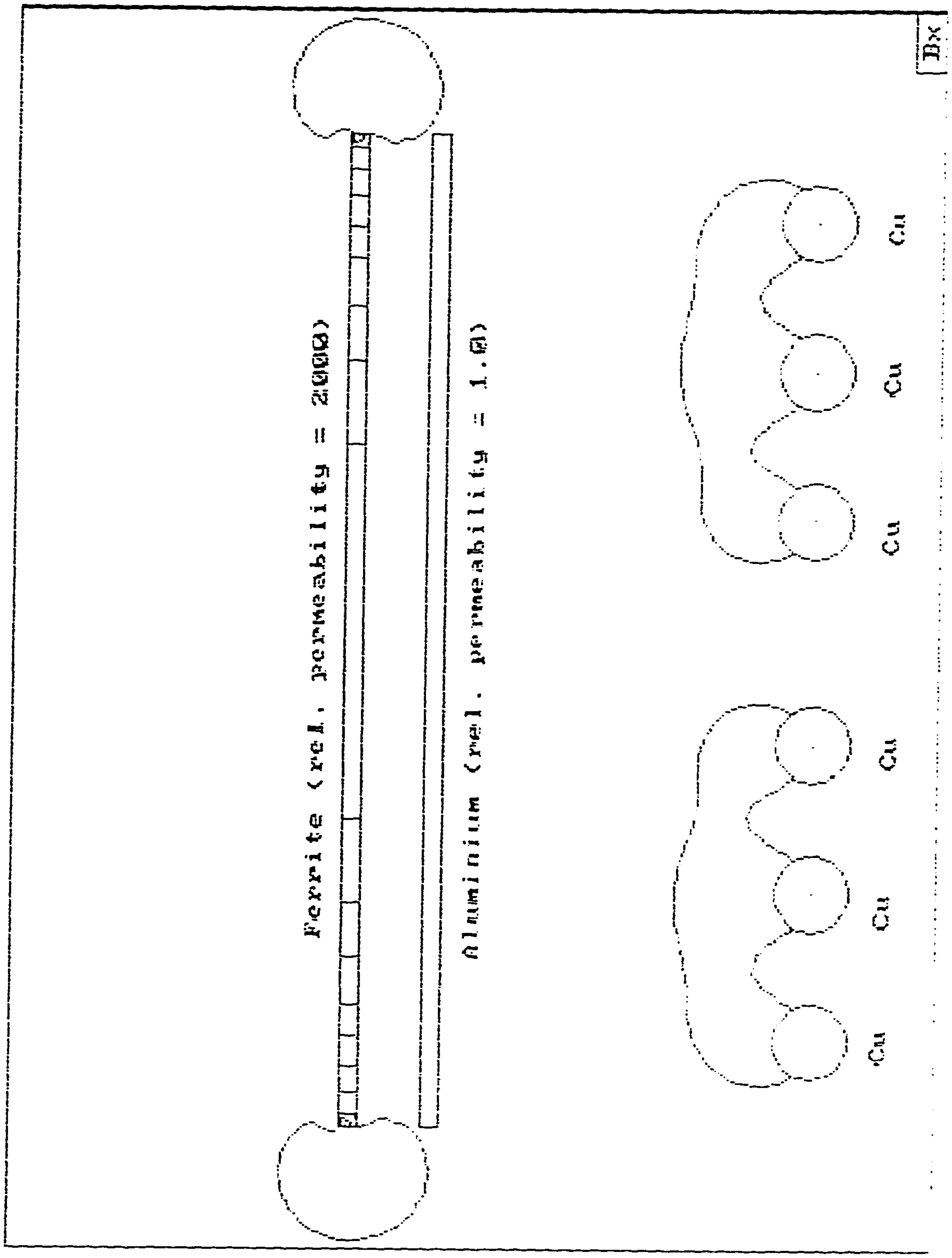


Figure 5.10: Contour Map(very fine density) - Case 2

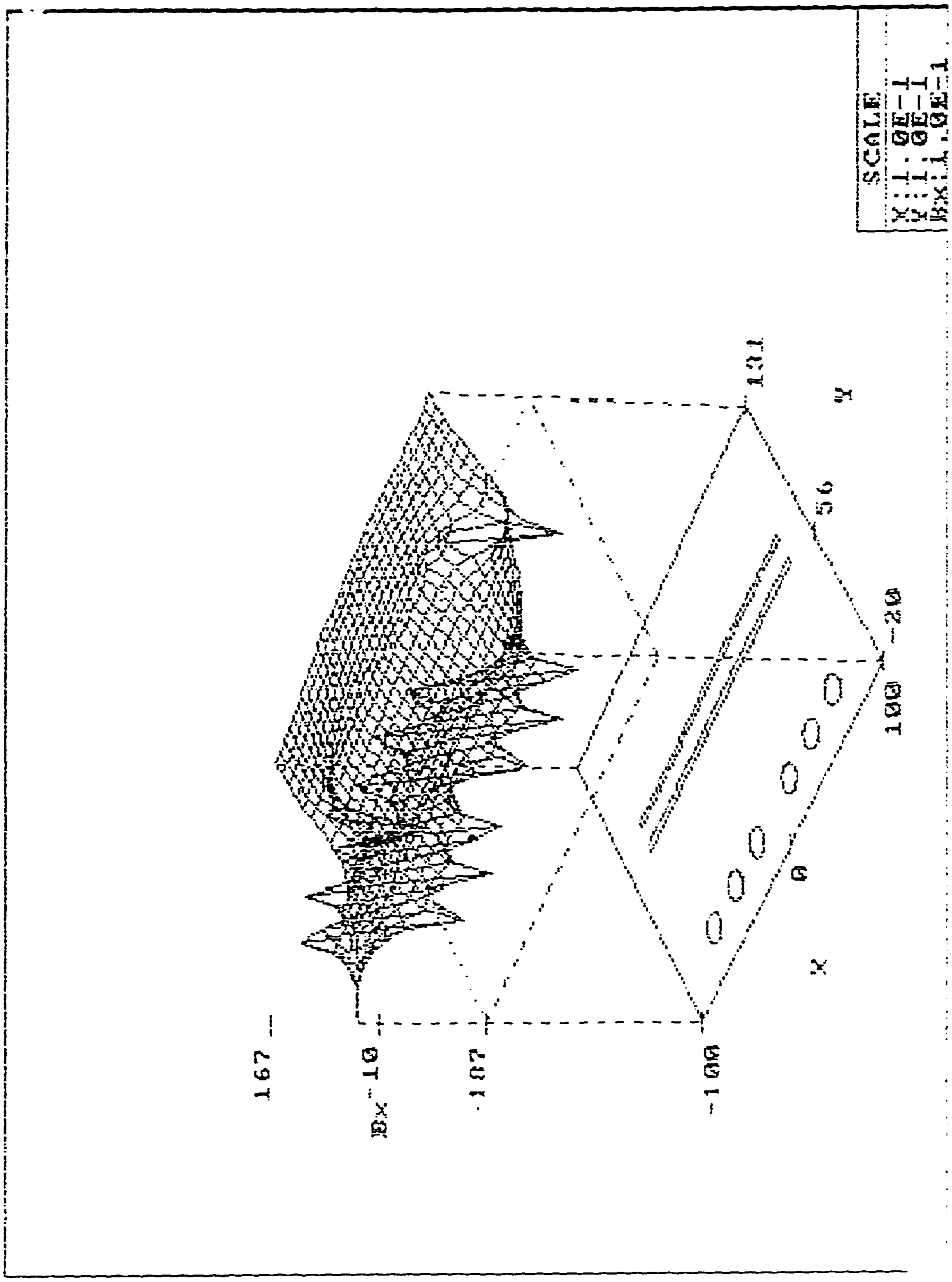


Figure 5.11: Profile Graph - Case 2

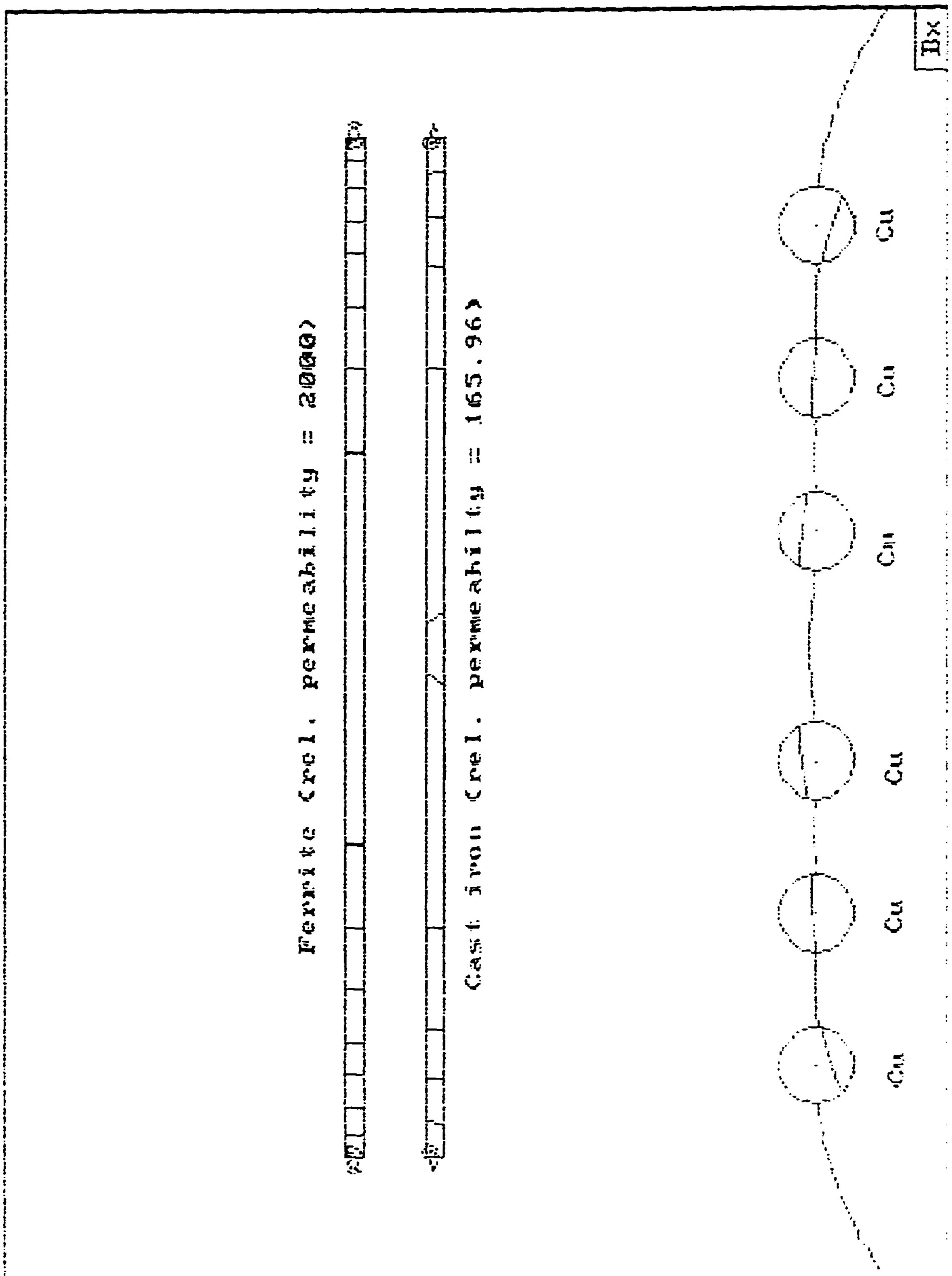


Figure 5.12: Contour Map(very fine density) - Case 3

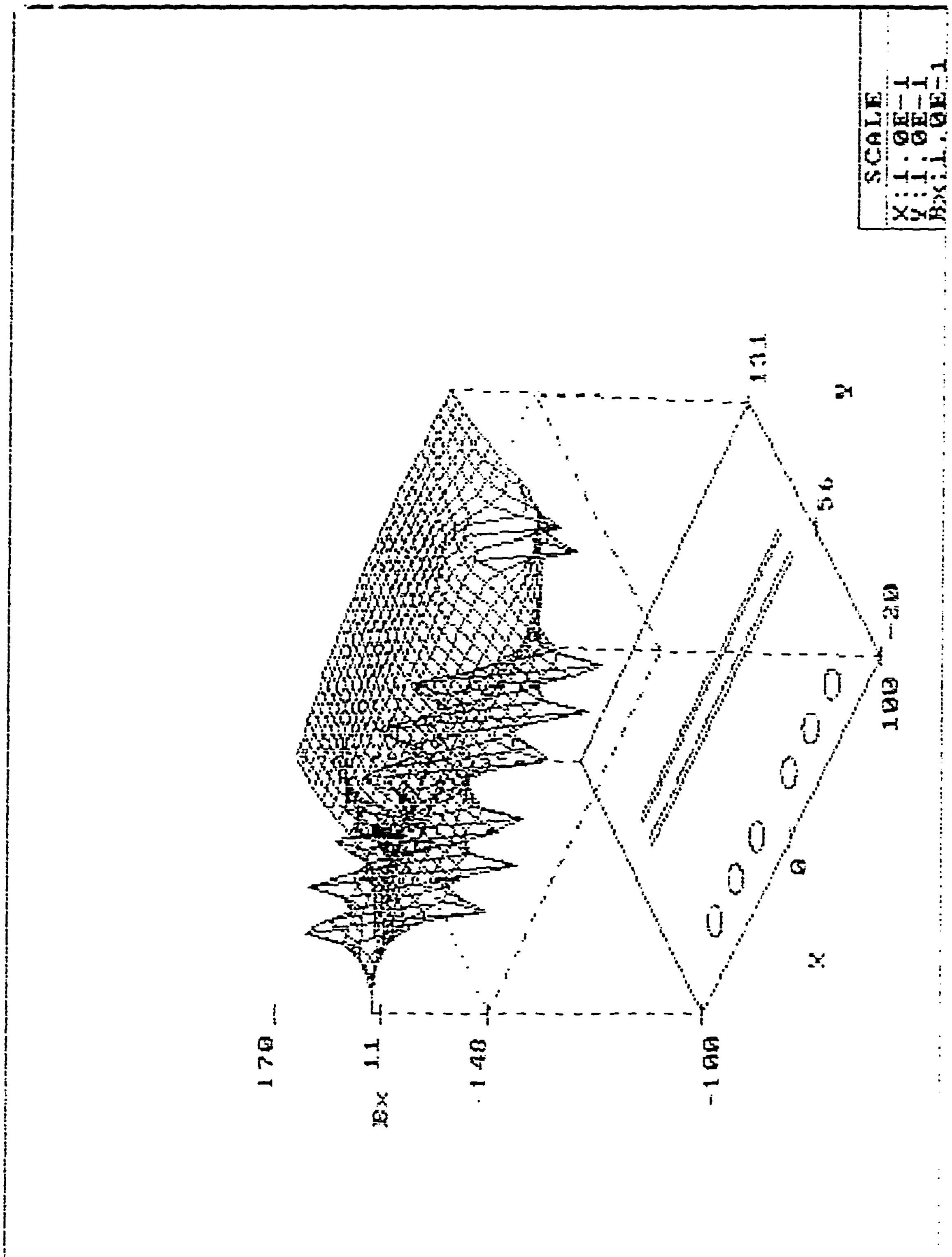


Figure 5.13: Profile Graph - Case 3

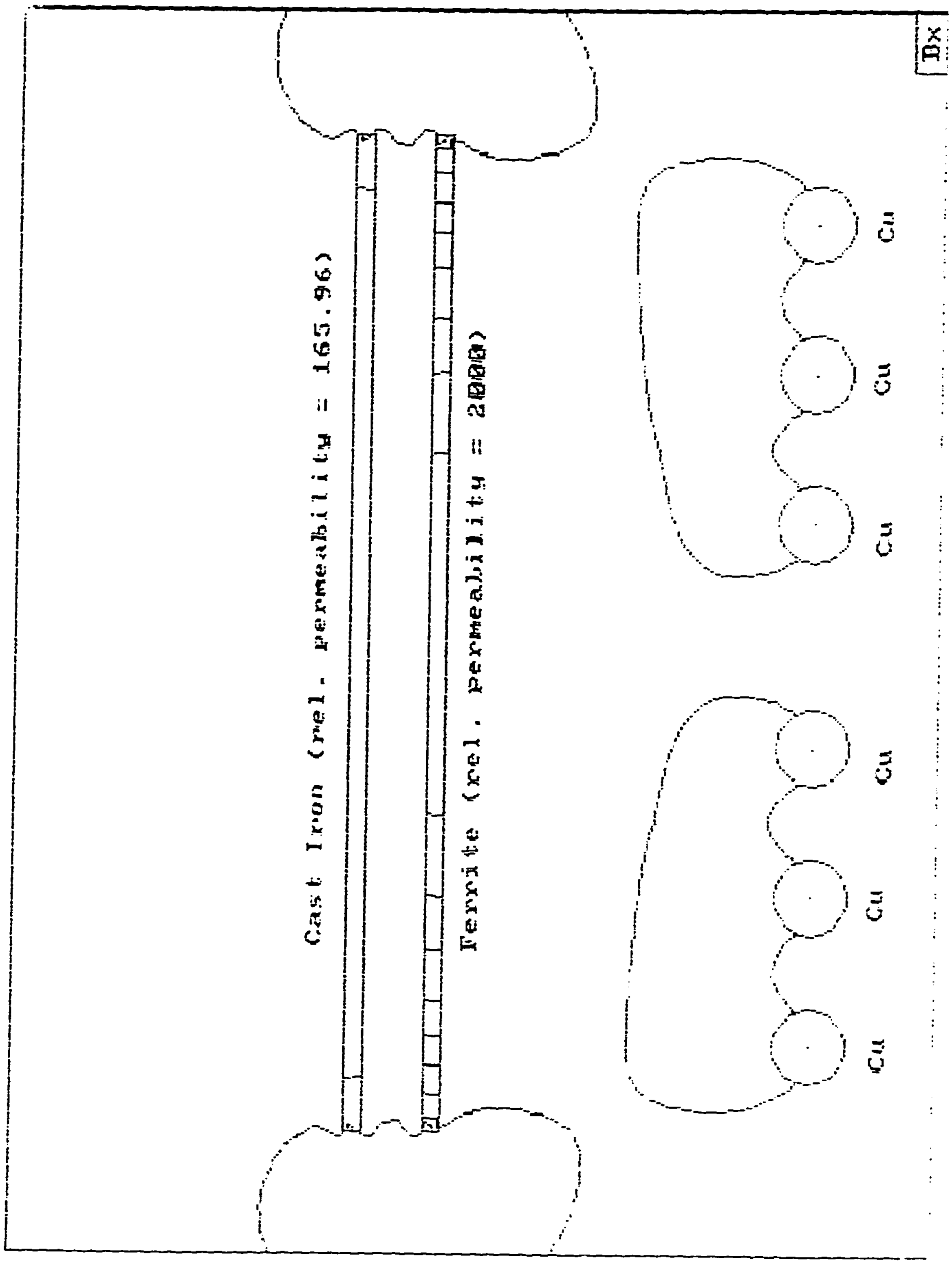


Figure 5.14: Contour Map(very fine density) - Case 4

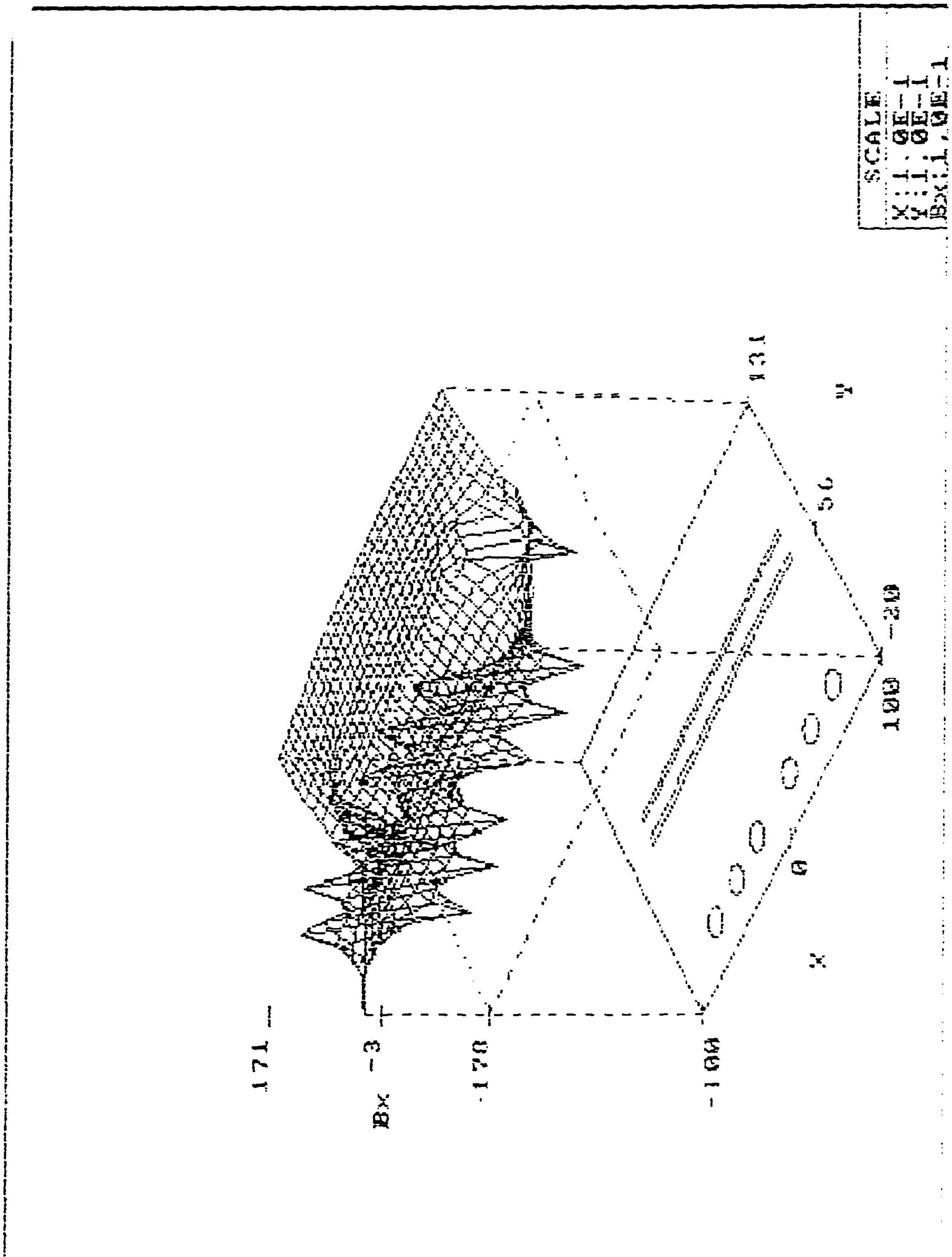


Figure 5.15: Profile Graph - Case 4

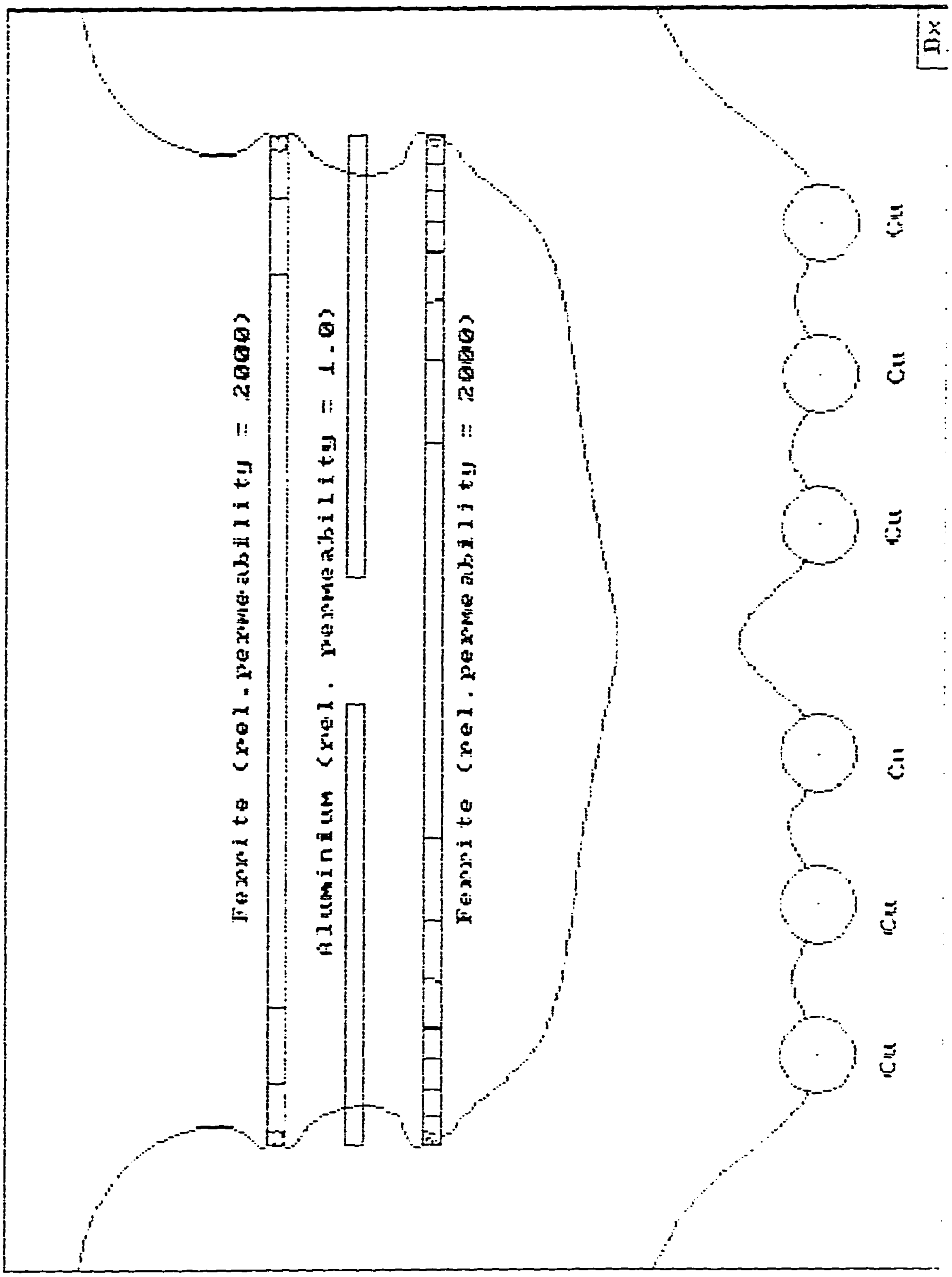


Figure 5.16: Contour Map(very fine density) - Case 5

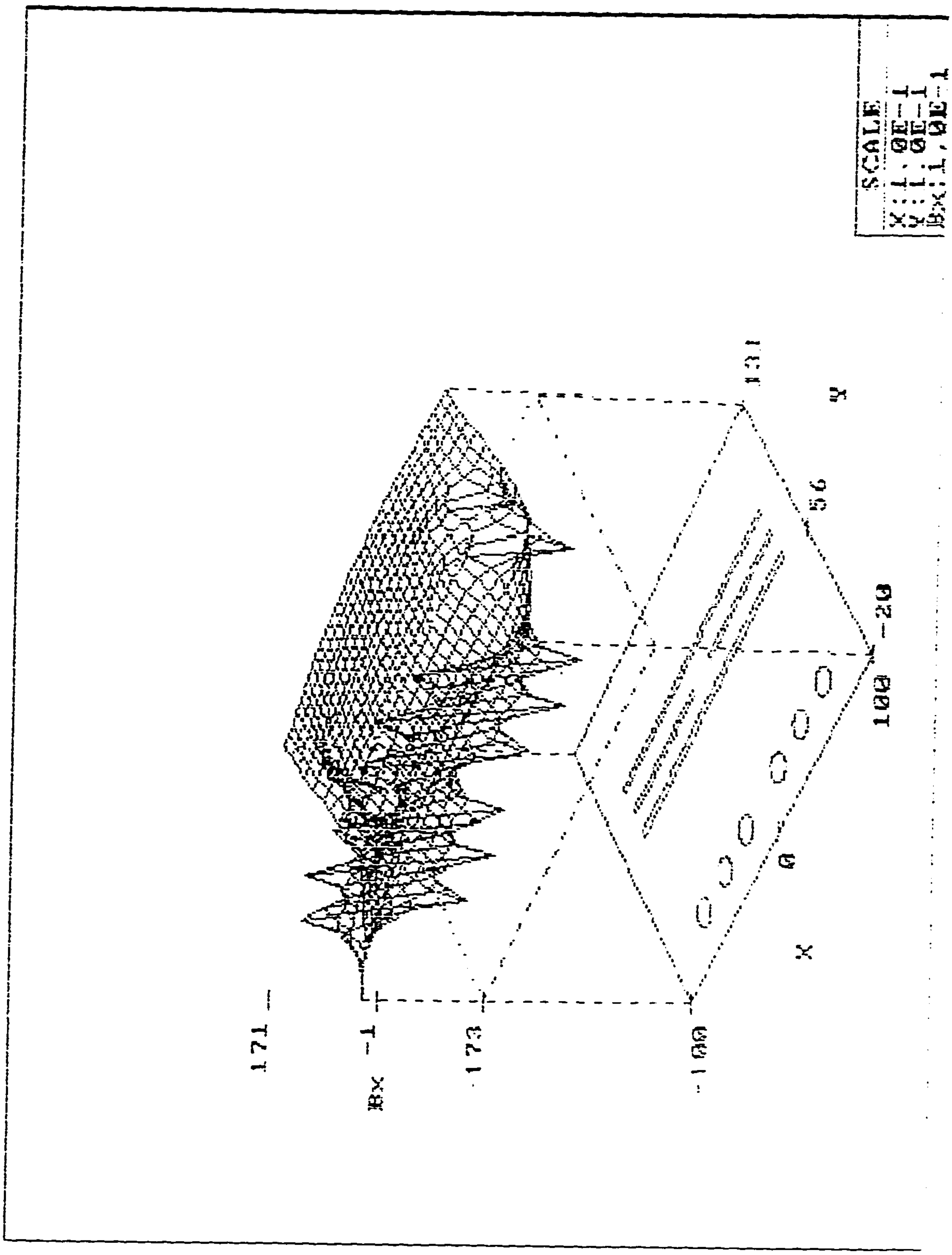


Figure 5.17: Profile Graph - Case 5

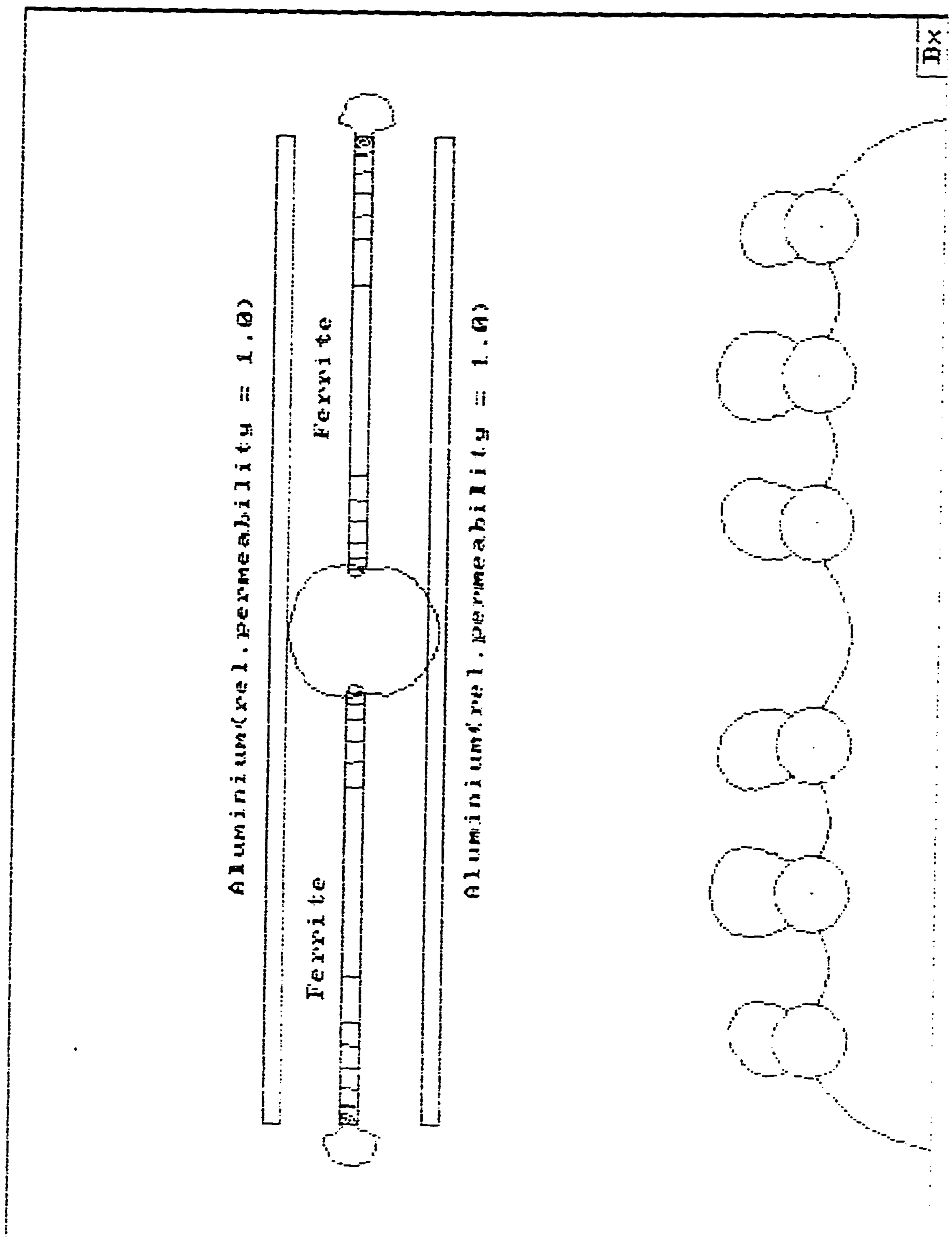


Figure 5.18: Contour Map(very fine density) - Case 6

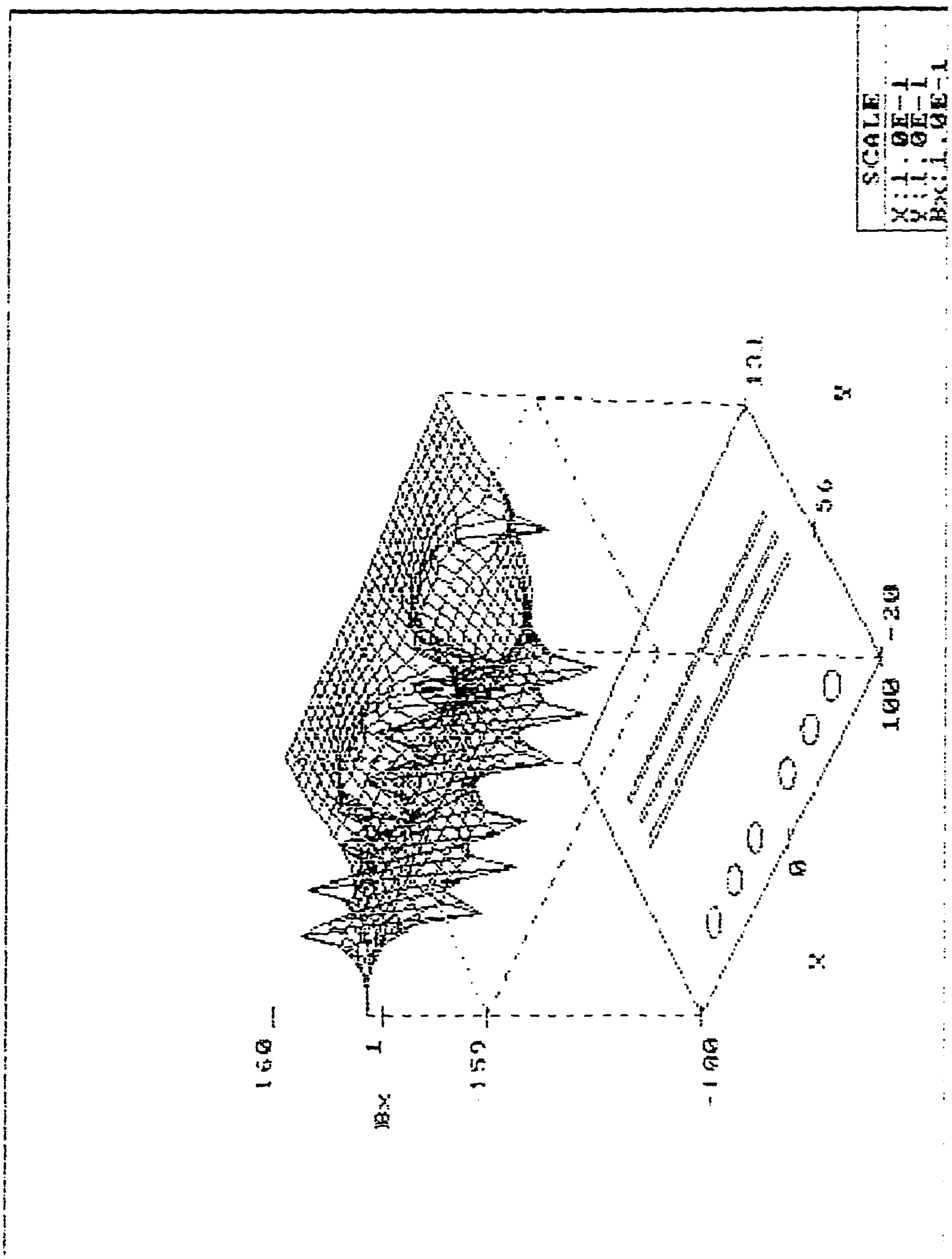


Figure 5.19: Profile Graph - Case 6

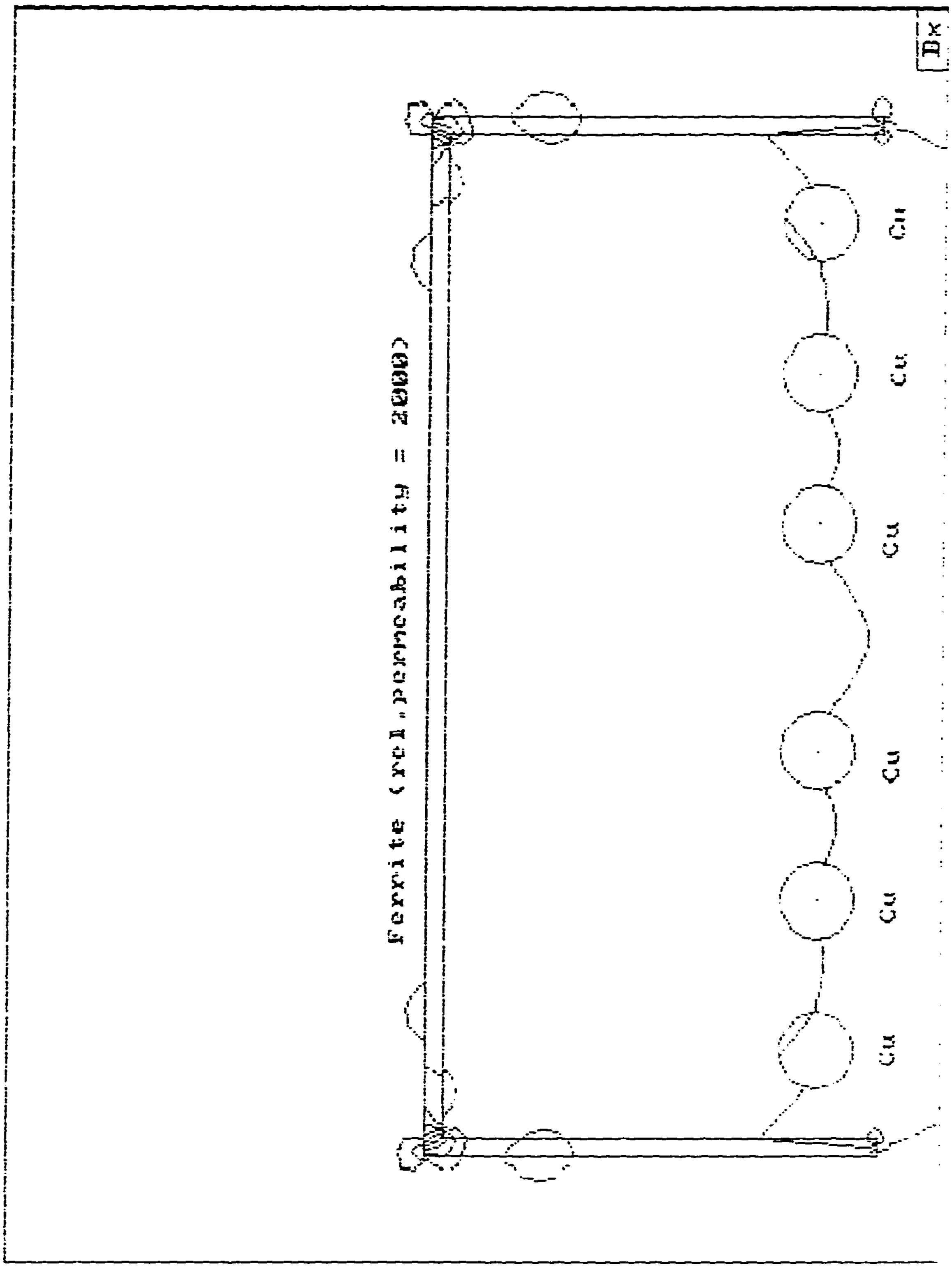


Figure 5.20: Contour Map(very fine density) - Case 7

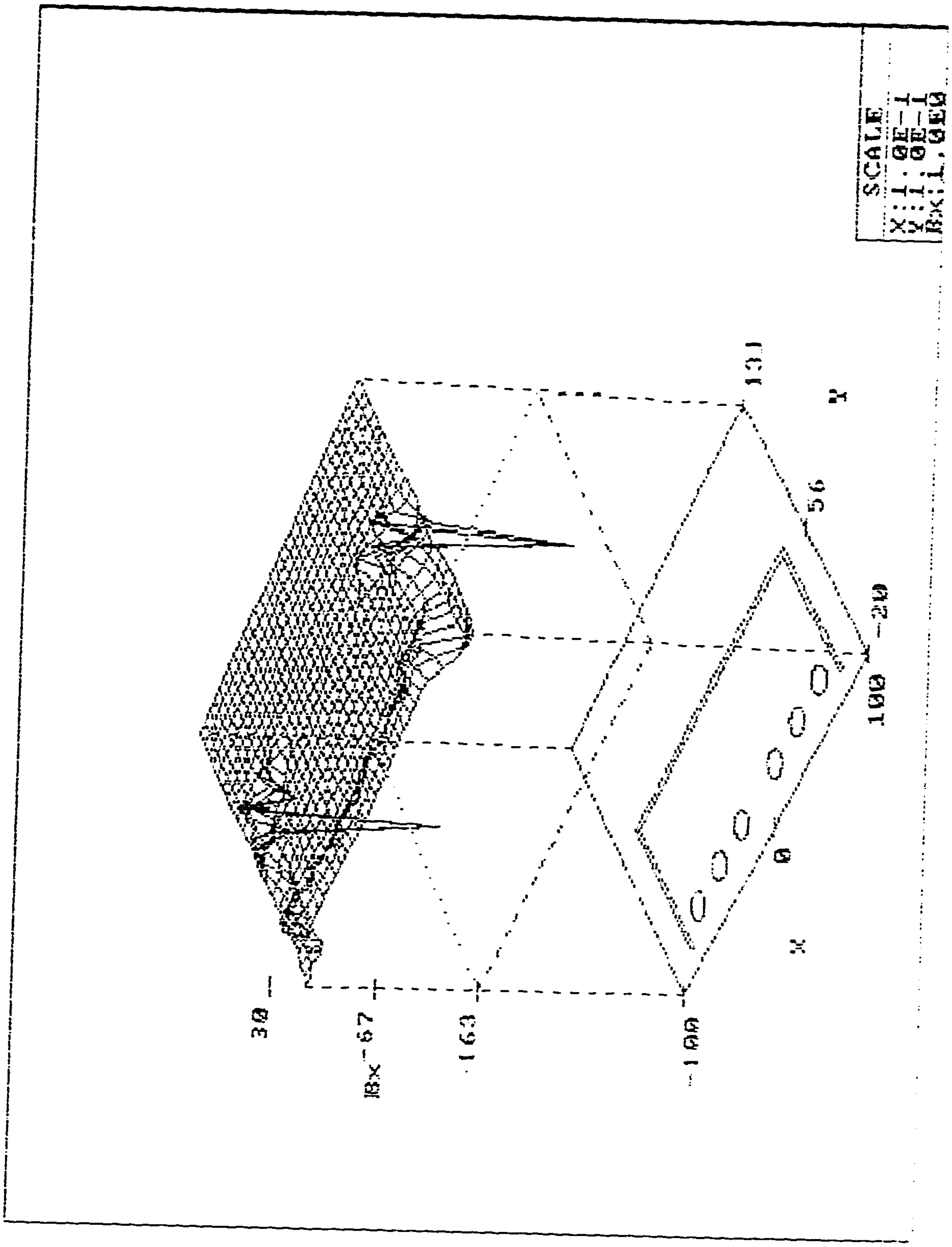


Figure 5.21: Profile Graph - Case 7

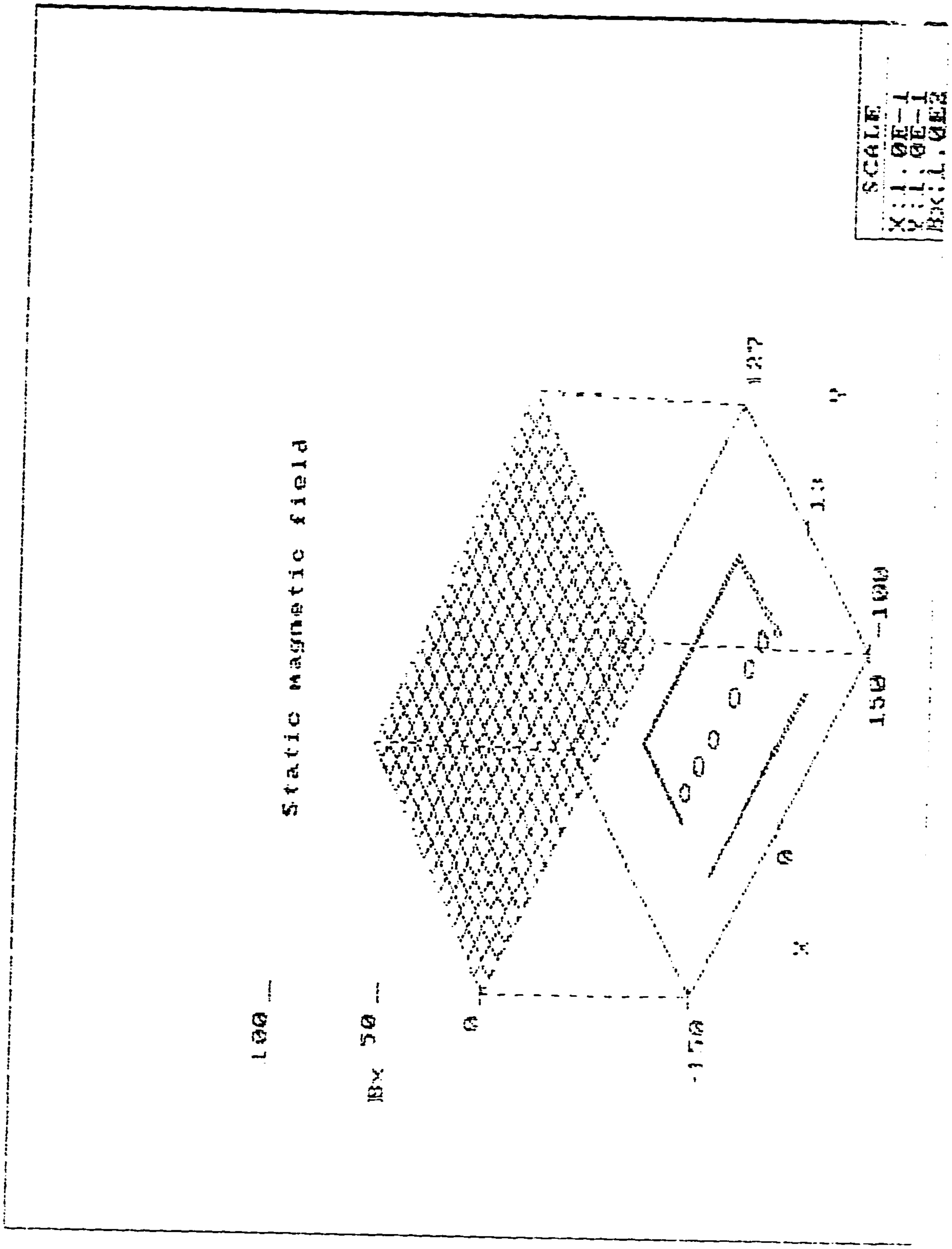


Figure 5.22: Profile Graph - Case 8

Chapter 6

Conclusions and Suggestions for Future Work

6.1 Conclusions

In this study one of the major sources of magnetic field which is the Underground Transmission and Distribution Cables has been identified. The state-of-the art magnetic field simulation packages (PCFIELD and MAGNETO) has been used to quantify and manage the field values due to underground cables. This study involves the application and evaluation of different engineering techniques and practices for managing the magnetic field levels in space surrounding the cables.

The standard EPRI's recommended cable configurations (stack, triangular and flat) has been modelled and simulated for six different cable sizes, both for single phase and three phase. Circuits as high as having 18 conductors (six cables per phase) starting from a double circuit line has been simulated and the results reported. Judicious placement of phases is a very powerful technique to reduce the field levels. For all the cases considered phase placement corresponding to minimal field is obtained and the results tabulated. For a single phase cable, the stack configuration gives minimum field for two, and four cables per phase, while the triangular configurations gives minimum field for three, five and six cables per phase. The flat configuration gives always the highest field. In case of three phase cables, two types of cable configurations, namely, the flat and the triangular are recommended and it is found that the flat configuration gives lesser field for two, four and five cables per phase. For three cables per phase the triangular configuration is most desirable. In case of six cables per phase for cable size up to 1.31 inch dia. (less than 500 MCM) the flat is preferred while for larger size cable (500 MCM or more) the triangular is preferred.

The second technique implemented for field management is increasing the depth of burial of the cables. The reduction in magnetic field values is limited to areas that are close to the center line of the cable. In other words the peaks are significantly reduced as they occur along the center line of the cable, at other places the fields are not very high. Increasing the depth of burial does little to decrease the field values at distances from the cable which are greater than several times the burial depth of the cable circuit. However, increasing the depth of burial leads to increased cost of installation and also has the detrimental effect of reducing the current carrying capacity of the cable circuit. Simulation has been done for three burial depths (3ft, 4ft and 5ft) and the results are reported.

Some new designs has been proposed in this work from the magnetic field point of view and the results obtained are very encouraging. Designs for two cables, three cables and four cables per phase has been shown and simulated for the magnetic field values. The field values obtained by the simulation package PCFIELD for these new designs are very low as compared to the EPRI's design. Moreover, the space in the structure can be utilized for the grounding conductors very conveniently in some these new designs.

One of the important work in the thesis was the implementation of the passive shielding technique for field management. This has been successfully implemented for the Source Shielding. Two plate thickness were taken and the result shows a very high value of shielding effectiveness. In some cases the reduction is as high as 98 %. Attempt has also been made to implement the Subject Shielding using MAGNETO simulation package. The package does simulate for the phase angles and as such the implementation is possible only for the d.c. sources. The trapping and field diversion are shown in the contour maps and the magnetic field profiles are drawn. Effect of different materials (different permeability) and different plate geometry has been investigated. Materials having good conductivity and high relative permeability are very effective for shielding purposes.

6.2 Suggestions for Future Work

Although the magnetic field management techniques have been implemented in this thesis work which can serve as a guideline to utility engineers, still there are some issues that has to be investigated and solved.

- For the unbalanced load conditions, investigation has to be done for magnetic field values.
- Accountability of neutral and ground currents for magnetic field modelling and simulations is an important issue. However, the software currently available does not model this problem.
- To achieve maximal shielding performance for a single conductor or unbalance in practical systems, a return-current path is needed. How parameters of a returned path affect magnetic field reduction is still questioned.

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